Glyphosate pathways to modern diseases V: Amino acid analogue of glycine in diverse proteins

Article in Journal of Biological Physics and Chemistry · June 2016

DOI: 10.4024/03SA16A.jbpc.16.01

2 authors:

Anthony Samsel

11 PUBLICATIONS **136** CITATIONS

SEE PROFILE

Stephanie Seneff

Massachusetts Institute of Technology

255 PUBLICATIONS **6,358** CITATIONS

SEE PROFILE

Glyphosate pathways to modern diseases V: Amino acid analogue of glycine in diverse proteins

Anthony Samsel[1, *] **and Stephanie Seneff**[2, **]

[1] *Research Scientist, Deerfield, NH 03037, USA*

[2] *Computer Science and Artificial Intelligence Laboratory, MIT, Cambridge, MA 02139, USA*

Glyphosate, a synthetic amino acid and analogue of glycine, is the most widely used biocide on the planet. Its presence in food for human consumption and animal feed is ubiquitous. Epidemiological studies have revealed a strong correlation between the increasing incidence in the United States of a large number of chronic diseases and the increased use of glyphosate herbicide on corn, soy and wheat crops. Glyphosate, acting as a glycine analogue, may be mistakenly incorporated into peptides during protein synthesis. A deep search of the research literature has revealed a number of protein classes that depend on conserved glycine residues for proper function. Glycine, the smallest amino acid, has unique properties that support flexibility and the ability to anchor to the plasma membrane or the cytoskeleton. Glyphosate substitution for conserved glycines can easily explain a link with diabetes, obesity, asthma, chronic obstructive pulmonary disease (COPD), pulmonary edema, adrenal insufficiency, hypothyroidism, Alzheimer's disease, amyotrophic lateral sclerosis (ALS), Parkinson's disease, prion diseases, lupus, mitochondrial disease, non-Hodgkin's lymphoma, neural tube defects, infertility, hypertension, glaucoma, osteoporosis, fatty liver disease and kidney failure. The correlation data together with the direct biological evidence make a compelling case for glyphosate action as a glycine analogue to account for much of glyphosate's toxicity. Glufosinate, an analogue of glutamate, likely exhibits an analogous toxicity mechanism. There is an urgent need to find an effective and economical way to grow crops without the use of glyphosate and glufosinate as herbicides.

1. INTRODUCTION

While it might be expected that fidelity is always perfect in mapping from the DNA triple code to the specific amino acid it codes for, multiple studies have shown that this is not the case [1–5]. In addition to coding errors leading to substitution of another core amino acid, there exist hundreds of non-protein amino acids that could be substituted, some of which occur naturally in plants [1, 2]. Others are produced as oxidation products of the original amino acids [3]. In inflammatory conditions such as Alzheimer's disease, atherosclerosis and cataract generation, accumulation of oxidized proteins as components of lipofuscin are believed to contribute to the disease process [6]. Remarkably, oxidized amino acids can be directly incorporated into protein chains through protein synthesis [4]. These damaged peptides cannot be repaired except through complete enzymatic hydrolysis, and their accumulation with aging is believed to disrupt cellular functions.

Finally, and most significantly, multiple *synthetically* produced amino acids, close structural analogues of natural amino acids, can be mistakenly incorporated into peptides [7, 3]. There are 20 unique aminoacyl-tRNA synthetases in the ribosomal system, each of which specifically recognizes one amino acid, according to the DNA code. Ominously, there does not appear to be any proof-reading mechanism for the ribosomal system. Once an amino acid analogue fools the recognition process, there is no mechanism to abort translation and discard an erroneously produced peptide sequence [4]. A direct quote from Rodgers et al. [4] makes this very clear: "Certain structural analogues of the protein amino acids can escape detection by the cellular machinery for protein synthesis and become misincorporated into the growing polypeptide chain of proteins to generate non-native proteins." Glyphosate is a glycine molecule with a methyl-phosphonyl group bound to the nitrogen atom. As an analogue of glycine, it can be expected to displace glycine at random points in the protein synthesis process, with unknown consequences.

Godballe et al. describe in their 2011 paper how glycine can be used to construct synthetic molecules

* Email: anthonysamsel@acoustictracks.net

** Corresponding author: S. Seneff, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, USA; e-mail: seneff@csail.mit.edu

Journal of Biological Physics and Chemistry **16** (2016) 9–46
Received 2 February 2016; *accepted* 31 March 2016

doi: 10.4024/03SA16A.jbpc.16.01

having functionality resembling the activities of cationic antimicrobial peptides [8]. A reactive side chain is attached to the nitrogen of glycine, and such units can be assembled into "peptoid" chains that in many ways resemble peptide chains, except that they are highly resistant to proteolysis. This is presumed to be beneficial because it allows the antimicrobial agent to survive longer in the tissues. These authors remarked: "N-substituted glycines can be viewed as amino acids, where the side chain is attached to the amine nitrogen instead of the α-carbon, and oligomers of these building blocks are called α-peptoids."

Glyphosate, is in fact, an N-substituted glycine; i.e., a peptoid unit. If glyphosate is misincorporated into a peptide under construction, it could interfere with the disassembly of the defective peptide, leading to the accumulation of undegraded short peptide chains with unknown consequences in the blood or in cells harbouring such defective proteins. It is intriguing and suggestive that phosphonyl groups are attractive as a component of designer peptides that inhibit proteases [9] and of potential insecticides that work by inhibiting protein degradation [10].

There is considerable evidence that glyphosate's biological effects are due in part to its action as a glycine analogue. Glyphosate disrupts chlorophyll synthesis in plants, likely due in (large) part to its inhibition of δ-aminolevulinic acid (ALA) synthesis, the rate-limiting step in the synthesis of the core pyrrole ring. It has been proposed that this may be a major factor, besides disruption of the shikimate pathway, in its toxicity to plants [11]. Its action as a glycine analogue likely causes competitive inhibition of ALA synthase from glycine and succinyl coenzyme A. Glyphosate has been shown to activate NMDA receptors in rat hippocampus [12], and this has been proposed to be in part due to glyphosate's ability to act as a ligand in place of glycine, in addition to glutamate (as the other ligand), whose overexpression is induced by glyphosate [13]. Both glyphosate and its metabolite aminomethylphosphonic acid (AMPA) can inhibit the growth of some tumour cells, likely by suppressing glycine synthesis [17].

If glyphosate substitutes for glycine in peptide sequences under construction, the results are likely to be catastrophic at multiple levels. The evidence that glyphosate interferes with glycine's rôles as a receptor ligand and as a substrate, and also suppresses glycine synthesis, implies that glyphosate could be taken up instead of glycine and subsequently incorporated into a peptide during protein synthesis. Several examples already exist of non-coding amino acids causing harm through misincorporation into peptides. For example, a natural non-coding amino acid analogue of proline, azetidine-2-carboxylic acid (Aze), is linked to multiple sclerosis due to its ability to displace proline in peptides [14]. Similarly, L-canavanine, a natural non-coding analogue of L-arginine, is a toxin stored in the seeds of certain plants [15, 16]. β-N-methylamino-L-alanine (BMAA), a natural analogue of serine synthesized by cyanobacteria, is implicated in amyotrophic lateral sclerosis (ALS) and other neurological diseases [1]. A recent study of glyphosate's effects on the rhizosphere microbiome showed sharp increases in the expression of proteins involved with both protein synthesis and especially protein degradation, implying that multiple synthesized proteins were failing to fold properly and had to be disassembled and reconstructed [18].

In this paper, we present a review of the literature on diverse biologically important proteins that contain either glycine-rich regions or conserved/invariant glycine residues. The evidence supports the likelihood that multiple diseases and conditions currently on the rise may be caused by disruption of conserved glycine residues, often in ways that would be predicted on the basis of glyphosate's physical properties.

Glycine plays many important rôles in human physiology, as an inhibitory neurotransmitter, as substrate for the biosyntheses of glutathione, haem, creatine, nucleic acids and uric acid, and as a source for one-carbon metabolism via the glycine cleavage system (GCS) [19]. Glycine also plays an important rôle in metabolic regulation and as an antioxidant. Finally, and perhaps most importantly, glycine is a highly conserved residue in diverse proteins, due to its unique properties. Glycine is the smallest amino acid, having no side chains. It is especially important in proteins that require flexibility, in hinge regions, or for ion gates that must open and close under varying circumstances [20]. Glycine is achiral, such that it can adopt angles representative of either L- or D-amino acids. Glycine confers flexibility through its unique ability to adopt a wide range of main-chain dihedral angles [21]. Many highly conserved glycine residues have been found in various proteins, reflecting this need for flexibility and mobility. It has also been determined empirically that substitution of conserved glycines in the enzyme acylphosphatase causes an increased tendency to aggregate, and this may be an important consideration for protection from the amyloid formation linked to many neurological diseases [22].

Glycine plays a critical rôle in dimerization for a number of protein classes for which dimerization is an essential step towards activation. Glycine is also highly conserved as the terminal residue in certain peptides, where it often plays a crucial rôle by supporting binding to the plasma membrane via myristoylation [23]. In many cases, even conservative substitution of alanine for

glycine disrupts the enzyme's function due to conformational changes following steric hindrance or impaired myristoylation. Conserved glycine residues are often located at the enzyme active site, particularly in the GXY or YXG motifs: glycine provides flexibility necessary to accommodate presence or absence of the substrate [24].

As of 2011, glyphosate was the largest selling herbicide worldwide [25]. In a series of previous publications [26–29], we have discussed how glyphosate's known toxicological mechanisms can be causal in a large number of diseases whose incidence is going up in step with the steadily increasing use of glyphosate on core corn, soy and wheat crops in the USA. The correlations between glyphosate usage and the recent alarming increase in multiple modern diseases are stunning, as presented in [30]. These include obesity, diabetes, end stage renal disease, renal failure, autism, Alzheimer's disease, dementia, Parkinson's disease, multiple sclerosis, intestinal infection, inflammatory bowel disease, stroke, leukemia, thyroid cancer, liver cancer, bladder cancer, pancreatic cancer and kidney cancer. Another study, looking at both human and animal data, revealed a large number of disorders of the newborn that are increasing in step with glyphosate usage [31]. These include congenital heart disease, skin disorders, genitourinary disorders, blood disorders, metabolic disorders and lung conditions. Our previous papers have been able to explain some of the pathology linked to glyphosate, predominantly through its powerful chelating effects, its adverse effects on beneficial gut microbes, its interference with the supply of crucial nutrients (in many cases derived from the shikimate pathway), and its suppression of cytochrome P450 enzymes in the liver.

However, given the large number of diseases and conditions that are correlated with glyphosate usage, we suspect that there is something much more insidious and fundamental than chelation or enzyme suppression that is happening with glyphosate. The fact that it is a synthetic amino acid, an analogue of an amino acid that carries many important rôles in the function of proteins containing it, makes it conceivable that glyphosate substitution for glycine in peptides could cause a large number of adverse effects that would not otherwise be anticipated. This would explain how a single toxic agent can be responsible for so many modern diseases.

2. BIOACCUMULATION, METABOLIZATION AND REACTION PRODUCTS OF GLYPHOSATE

The ability of glyphosate to bioaccumulate and metabolize *in vivo* in animals was clearly demonstrated in a 1988 study by Howe et al. [32]. Table 1 below outlines some of the study's design features. Seven groups of rats received a single oral or intravenous (IV) ^{14}C-radiolabeled dose of glyphosate technical acid (N-phosphonomethyl glycine). Group 6 was preconditioned with unlabeled glyphosate at 10 mg kg^{-1} day^{-1} for 14 days before receiving a single radiolabeled dose. AMPA and N-methyl AMPA (MAMPA) were the main metabolites found in the excreta, as well as other metabolites and reaction products. The fact that the research team found 0.3% of the dose as radioactive CO_2 in the expired air from the animals' lungs, within 24 hours, demonstrated *in vivo* metabolism. Glyphosate was the primary radiolabeled material found in the urine and faeces; bioaccumulation was found in all tissues, glands and organs. Additional details can be found in previously published work [29].

Table 1. Glyphosate metabolism experimental design by Howe et al. [32].

Group No.	Dose/ mg kg^{-1}	Animals	Route	Duration/ days	Samples collected
1	10	3 males 3 females	Oral	7	Urine, faeces, expired air @ 6, 12, 24 h
2	10	3 males 3 females	Oral	7	Blood @ 0.25, 0.5, 1, 2, 4, 6, 8, 12, 24, 48, 72, 120 and 168 h
7	10	3 males 3 females	IV	7	ditto
3	10	5 males 5 females	IV	7	Urine and faeces @ 6, 12, 24 h and daily thereafter; organs, tissues, carcass @ day 7
4	1000	5 males 5 females	Oral	7	ditto
5	10	5 males 5 females	Oral	7	ditto
6	10[a]	5 males 5 females	Oral	7	ditto

[a] Group 6 was preconditioned with unlabeled glyphosate at 10 mg kg^{-1} day^{-1} for 14 days before receiving a single radiolabeled dose.

Glyphosate metabolism by plants was also investigated by Dupont in 2007 [33]. Protection from the effects of glyphosate was achieved through genetic engineering of maize plants to induce excess synthesis of the enzyme glyphosate acetyltransferase (GAT). The modified gene, *gat4601*, produces the enzyme acetolactate synthase, which acetylates glyphosate, thus preventing herbicide activity and plant death. N-acetylglyphosate (N-acetyl-N-phosphonomethyl glycine) is another amino acid and glycine analogue that was found in animals by Monsanto.

Acetylation does not preclude glyphosate's incorporation as an amino acid. N-acetylglyphosate can be recycled back to glyphosate *in vivo* through deacetylation. This has been shown to occur in both goats [34] and chickens [35]. The metabolization of N-acetylglyphosate includes its decarboxylation to N-acetyl AMPA, and further metabolism to AMPA, as illustrated in Fig. 1. Radiolabeled metabolism of N-acetylglyphosate was investigated in chickens [35], using orally dosed laying hens. Sacrificed hens, eggs and excreta were analysed/assayed for total ^{14}C, glyphosate, AMPA, N-acetylglyphosate and N-acetyl AMPA residues. Results are shown in Table 2. The fact that nearly 12% of the reaction products in egg yolk were recovered in the pepsin digest, and over 3% in the protease digest, suggests that glyphosate is being incorporated into peptide chains. The ^{14}C radioactivity in the enzyme digests indicated that an additional glyphosate analogue had been extracted; however, low residue levels precluded further analysis.

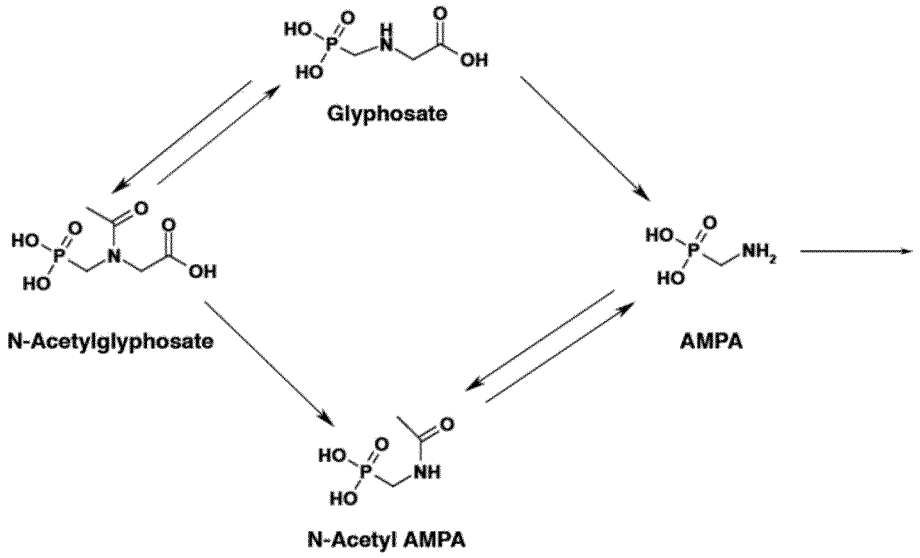

Figure 1. Glyphosate metabolism pathways.

Table 2. ^{14}C N-acetylglyphosate residues found in excreta, eggs and tissues (from Dupont, 2007 [35]).

Matrix	TRR[a]		Extracted		Unextracted	
	%dose	mg/kg eq[b]	%TRR	mg/kg eq	%TRR	mg/kg eq
Egg white	0.01	0.02	94.3	0.01	5.7	<0.01
Egg yolk	0.04	0.34	81.5	0.19	18.5	0.04[c]
Whole egg		0.36[d]	na[e]		na	
Liver	0.05	0.51	95.6	0.48	4.4	0.02[c]
Muscle		0.04	87.5	0.03	12.5	<0.01
Abdominalfat		0.05	92.4	0.05	7.6	<0.01
Excreta		84.1		83.2	1.0	
Cage wash		5.9		na		na
Total recovery		90.2[f]		na		na

[a] Total radioactive residue.
[b] Equivalent value derived from liquid scintillation data.
[c] Egg yolk and liver post-extraction solids (PES) were subjected to enzyme digestion.
[d] Levels in reconstructed whole eggs calculated by summing (proportionally) residue levels in egg whites and yolks.
[e] Not applicable.
[f] Total recovery was derived by summing radioactivity in excreta, cage wash, egg yolks, egg whites and liver.

Remarkably, in Dupont's study on goats [34], muscle extraction yielded only 42% of the total reactivity before pepsin digest, and there was negligible additional recovery after both pepsin and protease digests. This suggests that glyphosate strongly inhibited the ability of proteases to break down the proteins, as 58% remained embedded and detectable only by its radioactive label. It was also noted that liver extraction recovery was 83% before pepsin digest and 6.9% additional recovery after digest. Kidney extraction was 97% before pepsin with an additional 4.6% recovery from the digest. Omental, renal and subcutaneous fat yielded 35, 94 and 92% recovery, respectively, before pepsin digest with an additional 28% recovery from omental fat only by pepsin digestion. Protease digestion in these tissues yielded insignificant levels of TRR recovery.

The Lowery/Dupont experiment with 5 laying hens studied the metabolism of ^{14}C-radiolabeled N-acetyl-glyphosate [35]. Birds were dosed by capsule twice per day for seven days with pure N-acetylglyphosate. Two radiolabeled substances were found in the chicken excreta and identified by HPLC, N-acetylglyphosate 82%) and glyphosate (0.8%). Residues of N-acetyl-glyphosate, AMPA, glyphosate and N-acetyl AMPA were identified in the liver, as well as six distinct radiolabeled residues in the abdominal fat. Sequential treatment with pepsin and protease enzymes of the total radioactive residues (TRR) remaining in the liver and egg yolk samples liberated additional radioactivity (4.1–14.7% TRR *in toto*), suggesting that glyphosate had been incorporated into the proteins.

A total of eight radiolabeled substances were found in actual muscle tissue, including: N-acetylglyphosate 25% (0.009 mg/kg); AMPA 17% (0.005 mg/kg); glyphosate 7.2% (0.002 mg/kg); N-acetyl AMPA 1.9% (0.001 mg/kg); and four additional metabolites representing 9% (0.003 mg/kg).

The highest bioaccumulated total radioactive residue in whole eggs was 0.36 mg/kg, occurring at seven days. Unmetabolized N-acetylglyphosate and metabolites of AMPA, glyphosate and N-acetyl AMPA were 0.16, 0.002, 0.014 and 0.003 mg/kg, respectively.

Egg whites and yolks were also examined individually. The results are summarized in Table 3.

Table 3. Distribution of total radioactive residues (TRR) of glyphosate metabolites and reaction products found in chicken eggs and tissues by liquid scintillation counting (LSC).[a]

Component	Composite egg white (day 1–7)		Composite egg yolk (day 1–7)		Liver		Composite muscle		Composite fat	
	% TRR	mg/kg eq	% TRR	mg/kg eq	% TRR	mg/kg eq	% TRR	mg/kg eq	% TRR	mg/kg eq
TRR(mg/kgeq)	na	0.010		0.229		0.505		0.033		0.057
initial extract	94	0.009	81	0.187	96	0.483	87	0.029	92	0.053
concentrated extract	94	0.009	80[b]	0.183	64[c]	0.322	87	0.029	92	0.053
AMPA	-[d]	-	0.91	0.002	6.7	0.034	17	0.005	11	0.007
glyphosate	11	0.001	5.7	0.013	16	0.084	7.2	0.002	39	0.023
N-acetyl-AMPA	4.3	<0.001	1.1	0.003	4.0	0.020	1.9	0.001	10	0.006
N-acetyl-glyphosate	41	0.004	68	0.157	64	0.323	25	0.009	23	0.014
minor unknowns	3.4	< 0.001	-	-	-	-	15[e]	0.006	1.4[f]	0.001
pepsin digest (PD)	na[g]	na	12	0.027	3.8	0.019	na	na	na	na
processed PD	na	na	4.3[h]	0.010	0.63[h]	0.003	na	na	na	na
protease digest	na	na	3.1[h]	0.007	0.27[h]	0.001	na	na	na	na
unextracted residues	5.7	0.001	3.8	0.008	0.36	0.002	13	0.004	7.6	0.004

[a] From Dupont, 2007 [35].
[b] Differences during processing reflect losses (1.5% TRR) incurred during concentration and/or sample clean-up for HPLC.
[c] Losses (32% TRR) during the process were attributed to non-selective adsorption to particulate matter in the concentrated extract.
[d] Not detected.
[e] Not applicable.
[f] Up to 4 components with no one component accounting for greater than 9% TRR (0.003 mg/kg eq).
[g] Up to 2 components with no one component accounting for greater than 0.7% TRR (< 0.001 mg/kg eq).
[h] Low levels of radioactivity in the concentrated digest precluded further characterization.

Glyphosate, like the canonical amino acids, is capable of chemical modification and metabolism *in vivo* [29]. The glyphosate amino acid analogues that are reaction products of these processes are shown in Fig. 2. Glyphosate can be acetylated, methylated, formylated and nitrosylated. Enzymatic deacetylation also recycles the acetylated molecule back to glyphosate. All of these modifications will impact the potential for glyphosate to be taken up by the cell and will change its reaction chemistry. For example, amino acid methylation generally makes the molecule both more water-soluble and more fat-soluble, as well as lowering the activation energy [36]. Fig. 3 shows metabolites of glyphosate that were found during Monsanto's experiments on rats. N-acetyl AMPA was identified by Dupont.

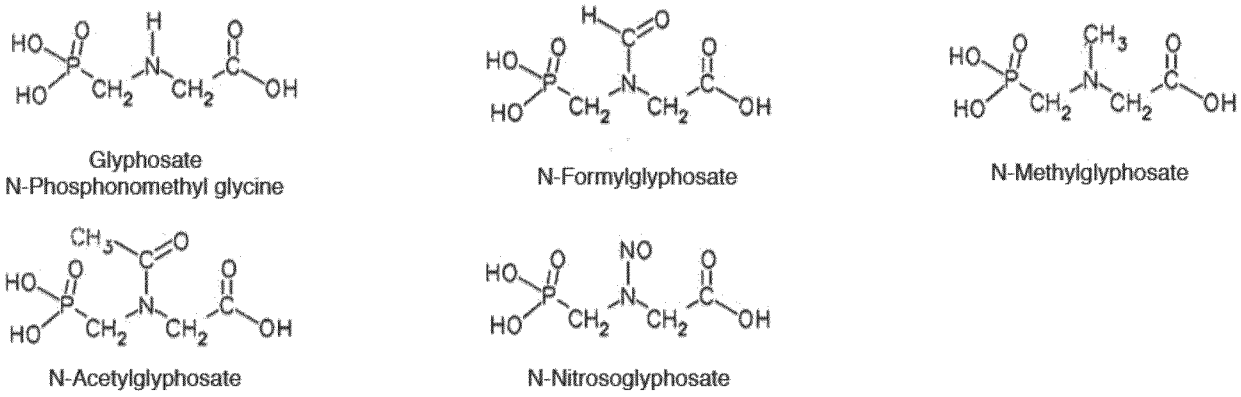

Figure 2. Glyphosate-derived amino acids identified by Monsanto exhibiting typical amino acid modifications.

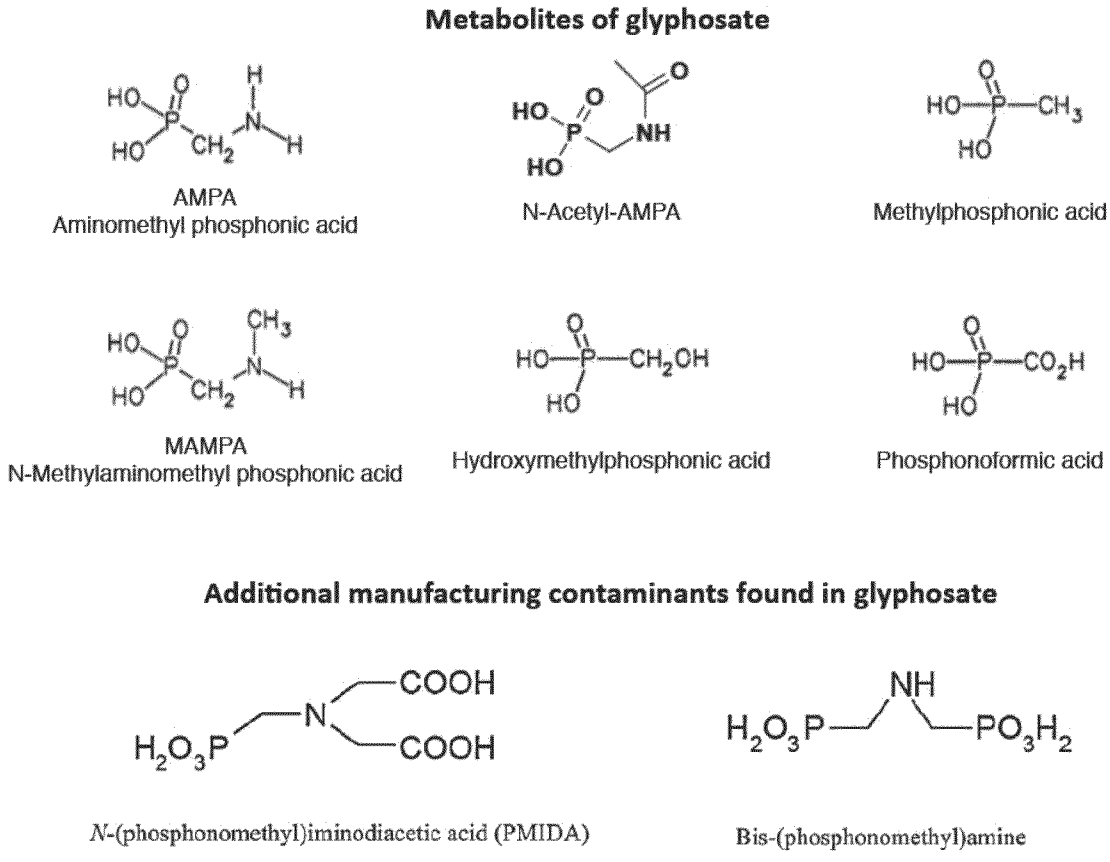

Figure 3. Metabolites and manufacturing contaminants of glyphosate.

3. DNA DAMAGE: CHROMATID DELETIONS AND ACHROMATIC LESIONS

One of Monsanto's early studies involved examining DNA damage in bone marrow of mice exposed to glyphosate [37]. An interesting finding was a substantial increase in the number of chromatid deletions and achromatic lesions observed following glyphosate exposure compared to controls (Table 4). Achromatic lesions (gaps) in chromatids are induced by endonucleases that play a rôle in the repair process. These gaps are a manifestation of unrejoined DNA double-strand breaks following endonuclease activity [38]. A possible explanation for the observed lesions involves impaired DNA repair mechanisms, particularly concerning the nucleotide guanine. 7,8-dihydro-8-oxoguanine (8-oxoG) is one of the most commonly formed oxidative lesions in DNA [39]. It is particularly destructive because it mispairs with adenine during replication, changing guanine:cytosine to thymine:adenine. Premutagenic lesions accumulate in mice that are defective in the gene coding the DNA glycosylase enzyme, OGG1, which excises 8-oxoguanine from DNA [40].

Table 4. Statistical analysis of data on chromatid deletions and achromatic lesions in rat bone marrow cells, performed only on data where the observed frequency for glyphosate treatment was higher than that of the solvent control.[a]

A. Chromatid deletions: observed frequencies[b]			
Sampling time	Control	Glyphosate (1g/kg)	p^c
12 h	0.0035	0.0087	0.26
24 h	0.0071	0.0142	0.26
B. Achromatic lesions: observed frequencies[b]			
Sampling time	Control	Glyphosate	p^c
6 h	0.0083	0.020	0.08
12 h	0.0052	0.016	0.08

[a] Table reproduced from Monsanto's 1983 report [37].
[b] No. of aberrations minus number of cells scored.
[c] Probability to be the same as the solvent control as determined by Student's *t* test.

Clustered DNA damage means multiple lesions in close proximity. In particular, it has been demonstrated experimentally that a lesion adjacent to an 8-oxoG is more resistant to the endonuclease-based repair process [41]. OGG1 has a conserved glycine at position G42 that plays an essential rôle in distinguishing 8-oxoG from guanine [42]. A hydrogen atom binds to the N7 atom of guanine during the formation of 8-oxoG, and this hydrogen atom is H-bonded to the carbonyl of the strictly conserved glycine residue in OGG1 to secure attachment. That is how it can recognize the oxidized form of guanine and distinguish it from the healthy, unoxidized molecule. Substitution of alanine for G42 disrupts the binding due to steric hindrance. With OGG1 impaired through glyphosate substitution for glycine, one can expect an accumulation of unrepaired 8-oxoG, leading to an increased frequency of clustered DNA damage and double strand breaks, and therefore of chromatid deletions and achromatic lesions, as observed by the Monsanto researchers. Mice with impaired OGG1 function develop increased adiposity, fatty liver disease and impaired glucose tolerance [39]. A defective version of this gene is linked to type-II diabetes in humans [43, 44].

4. METABOLIC AND SIGNALING DISORDERS

In this section we will examine several classes of enzymes that contain conserved glycines with essential rôles. We show that glyphosate substitution for glycine in hormone-sensitive lipase can explain an association between glyphosate and obesity, as well as adrenal insufficiency. The combination of protease inhibition and enhanced kinase activity can be predicted to cause excessive phosphorylation systemically. Phosphorylation is a widespread modification with profound effects on affected molecules, which can increase risk to both Alzheimer's disease and cancer. Pulmonary oedema induced by glyphosate can be explained through protein phosphatase inhibition.

The insulin receptor has conserved glycines that are necessary for its transport from the endoplasmic reticulum (ER) to the plasma membrane. Insufficient insulin receptor availability leads to hyperglycaemia and diabetes. Cytochrome c oxidase (COX) is the enzyme responsible for the final step of ATP synthesis in the mitochondrion. Substitutions for conserved glycines in COX severely impair oxidative phosphorylation. This can explain glyphosate's known toxicity to mitochondria. Kelch-like ECH-associated protein 1 (KEAP1) is a protein that regulates nuclear factor erythroid 2-related factor 2 (Nrf2)-like activity. It depends on a conserved glycine to prevent Nrf2 migration into the nucleus to activate multiple genes. Nrf2 overactivity can directly explain the beak deformities observed in chickadees fed sunflower seeds that were sprayed with glyphosate just before harvest. Nrf2 overactivity is also linked to fatty liver disease.

Hypothyroidism in the mother is a risk factor for autism in the child [45]. Disruption of conserved glycines in the pituitary gland can lead to insufficient release of thyroid-stimulating hormone. Conserved glycines also play a rôle in adrenocorticotropic hormone (ACTH) release, and ACTH deficiency has been linked to adrenal

insufficiency induced by glyphosate [46]. Both sulfate synthesis by endothelial nitric oxide synthase (eNOS) and the removal of sulfate from bioactive sulfated molecules can be predicted to be impaired upon glyphosate for glycine substitution at critical locations on eNOS and arylsulfatases. eNOS also depends on conserved glycines for nitric oxide synthesis. Impaired nitric oxide synthesis leads to hypertension.

4.1 Impaired cholesterol and fat metabolism

Lipases and esterases are an important group of enzymes that hydrolyse ester bonds. They contain a characteristic gly-xaa-ser-xaa-gly (GXSXG) motif; the essential active serine residue imparts the name "serine hydrolases" [47]. The hydrogen bond donated by the first glycine of the motif plays a critical rôle in the catalysis [48–50]. An especially interesting subclass of serine hydrolases are the hormone-sensitive lipases (HSLs) which, in humans, are responsible both for lipid hydrolysis and cholesterol ester hydrolysis [51]. HSLs respond to adrenalin, catecholamines and ACTH by initiating the release of fatty acids from adipose tissue as a source of fuel for the tissues [52]. HSLs are closely related to several bacterial proteins [53–55], and more distantly related to acetylcholinesterase and lipoprotein lipase. Hydrolase disruption leads to lipotoxic effects that can promote mitochondrial dysfunction, induce endoplasmic reticulum (ER) stress, induce inflammation, and compromise membrane function leading to apoptosis [56]. Impaired HSL function has been linked to obesity, atherosclerosis and type 2 diabetes [51].

In addition to the conserved GXSXG motif, members of the mammalian HSL class also contain the tetrapeptide histidyl-glycyl-glycyl-glycine (HGGG) motif in a conserved region described as an "oxyanion hole" [57, 58]. This is a critical element in the catalytic machinery of diverse proteolytic enzymes (notably serine protease and certain caspases), which stabilizes negative charge build-up in the substrate via hydrogen bonds.

Monsanto's chronic studies in mice and rats cited in our previous work [29] found considerable tissue destruction by glyphosate in the pituitary, thyroid, thalamus, testes and adrenal glands, as well as major organs. A 1990 study by Stout and Rueker revealed significant cortical adenomas, benign and metastatic pheochromocytomas and ganglioneuromas in male and female animals. A 1983 Knezevich and Hogan chronic study of glyphosate in mice revealed lymphoreticular tumours that "tended to be more frequent in treated animals, particularly the females." It revealed cortical cell adenoma and lymphoblastic lymphosarcoma of the adrenals.

A previous 1982 chronic study in rats by Lankas and Hogan also showed neoplastic phenomena in the adrenals, including reticulum cell sarcoma, pheochromocytoma, cortical adenomas and malignant lymphoma of the adrenals particularly in the female animals. "Pheochromocytoma of the adrenals was the second most common tumour found among male animals. Most frequent neoplastic changes of glands was seen in the pituitary gland which was highest in females" [59].

HSLs play an essential rôle in the adrenal glands as a first step in adrenal hormone synthesis from cholesterol [60]. The glyphosate-containing herbicide Roundup has been shown experimentally to severely impair adrenal hormone synthesis [46]. A glyphosate substitution for glycine in the GXSXG motif and/or the HGGG motif would disrupt protein function. This would also explain a link between glyphosate and obesity, due to impaired release of stored fats. The correlation between Roundup use on corn and soy crops and obesity in the USA as determined by data from the Centers for Disease Control (CDC) is very strong ($R = 0.96$, $P = 2 \times 10^{-8}$) [30].

4.2 Protease inhibition

Because excess expression of metalloproteinases is implicated in metastatic cancer, there is considerable interest in developing compounds that can inhibit protease activity [61]. Much effort has gone into developing protease inhibitors based on a phosphonyl moiety [9, 62]. The discovery of very potent irreversible inhibitors based on phosphonyl fluoride led to their use in *in vitro* studies, but they are highly unsuitable for therapeutic inhibition because they react with acetylcholinesterase, making them extremely toxic. Glyphosate, like phosphonyl fluoride compounds, has also been shown to inhibit acetylcholinesterase [63].

As a consequence of the toxicity of phosphonyl fluoride-based protease inhibitors, there has been a focus shift towards the concept of *peptidyl* phosphonate esters, because these can be hydrolysed, and because they can be designed to be specific to a narrow class of proteases. The attached polypeptide chain can be tuned to match the specificity of the target enzyme. Their mechanism of action is complex, but it involves a stable tetravalent phosphonylated derivative where one of the phosphonate oxygens is extended into an oxyanion hole (details can be found in [9] in the section beginning on p. 90). It can be expected that glyphosate's phosphonyl group might have a similar effect and, because of glyphosate insertion into a large number of different peptide sequences, the consequence of inhibition of multiple proteases by various glyphosate-containing short peptide chains, with unpredictable outcomes, can be expected.

4.3 Protein kinases, cancer and Alzheimer's disease

The human genome contains about 518 putative protein kinase genes, which constitute about 2% of all human genes [64]. Protein kinases contain a glycine-rich domain in the vicinity of the ATP-binding lysine residue in the N-terminal domain. The glycine-rich loop anchors the phosphate of ATP in a cleft just below the loop, and the nearby positively charged conserved lysine secures the nucleotide in place [65]. Protein kinase CK2 is a highly versatile molecule, able to phosphorylate more than 160 substrates on serine, threonine and tyrosine, using both ATP and GTP as phosphate donors [66]. It is involved in signal transduction and cell cycle regulation, cell proliferation and oncogenesis. A conserved region contains a glycine-rich loop (GXGXXG) that is also found in other protein kinases [67]. A model has proposed that the GXGXXG residues form an elbow around the nucleotide [68]. The second glycine, G48, is conserved in 99% of protein kinases, and it plays a fundamental rôle. Its replacement by negatively charged residues gives rise to mutants with improved kinetic properties for the peptide substrates. Insertion of a negatively charged residue favours faster release of ADP from the ATP pocket, leading to increased activity. It can be expected that glyphosate substituting for any of the conserved glycines in protein kinases, but especially G48, will *increase* protein activity.

Cyclin-dependent kinases (CDKs) are central to control of eukaryotic cell division. Their activity is regulated through phosphorylation and dephosphorylation of conserved threonine and tyrsosine residues [69]. GEGTYG is a highly conserved motif in CDK1, CDK2, CDK3, CDK5 and CDK10 [70]. This motif is referred to as the "G-loop," and the adjacent glycines are essential for maintaining the flexibility to control activation/inactivation by phosphorylation of the intervening threonine and tyrosine in the sequence GTYG. All the CDKs except CDK7 maintain the motif GXGXXG.

It has been suggested that overactivity of protein kinase CK2 plays an important rôle in cancer [71]: CK2 overexpression protects cellular proteins from caspase action and subsequent apoptosis. This leads to the transformation to a tumorigenic form supporting survival and proliferation. Imatinib (Gleevec) is a remarkably effective tyrosine kinase inhibitor used in chemotherapy to treat patients with leukaemia and breast cancer [72]. Many other drugs based on suppression of protein phosphorylation are under development [73].

Glycogen synthase kinase 3 (GSK3) is a constitutively active, proline-directed serine/threonine kinase, also containing a highly conserved glycine-rich N-terminus [74]. Its overexpression has been linked to Alzheimer's disease [75]. Overexpression of GSK3 can result in the hyperphosphorylation of tau, memory impairment, the increased production of β-amyloid (Aβ) and in the inflammatory response. GSK3 also reduces acetylcholine synthesis, and cholinergic deficit is a feature of Alzheimer's disease [76]. GSK3 also mediates apoptosis, which will promote the loss of neurons.

4.4 Insulin receptor activity and diabetes

The insulin receptor (IR) is a transmembrane tyrosine kinase receptor activated by both insulin and the insulin-like growth factors IGF-I and IGF-II. Defective IR activity can lead to type 2 diabetes [77], which has reached epidemic proportions throughout the industrialized world. The incidence of diabetes has been going up over time in the USA exactly in step with the increased use of glyphosate on core crops [30]. Knockout studies on mice, in which the insulin receptor of the α-cells of the pancreas were impaired, demonstrated that glucagon release is regulated by these receptors and, when they are dysfunctional, the mice display hyperglucagonaemia, hyperglycaemia and glucose intolerance [78]. A significant incidence of pancreatic islet cell tumours were reported in Monsanto studies in 1981 and 1990 (data shown in [29]).

A loosely conserved motif in two families of receptor tyrosine kinases, insulin receptors and epidermal growth factor receptors is characterized by a central glycine residue that allows for a turn in the secondary structure of the protein [79]. This glycine residue has an upstream α-helix and a downstream β-sheet. Receptors for insulin and epidermal growth factor both contain at least 8 repeats of this motif. The glycine-centred motif in the IR is thus very important in determining its three-dimensional structure [80]. A patient with leprechaunism, a genetic syndrome associated with extreme insulin resistance, had two mutations in the gene for IR, one of which was a glycine in this conserved loop [81]. Arginine was substituted for gly366 in the first repeat of the loop, and alanine displaced a conserved hydrophobic valine residue. Both mutations impair post-translational processing and intracellular transport of the receptors to the plasma membrane. Most likely, these two mutations inhibit the folding of the proreceptor into its normal conformation [80]. This results in its retention within the ER, and therefore post-translational processing steps in the Golgi apparatus are blocked. The result is a great reduction in the number of receptors that are transported to the plasma membrane and, therefore, impaired glucose uptake.

4.5 Cytochrome c oxidase

Glyphosate has been shown to disrupt oxidative phosphorylation in mitochondria, although this effect required dosages that were much higher than would be expected in realistic physiological situations [82]. Glyphosate in combination with surfactants has been shown to cause mitochondrial damage and induce apoptosis and necrosis [83]. It is possible that glyphosate induces toxicity to mitochondria through an effect on cytochrome c oxidase (COX), and that the surfactants enable glyphosate's entry into the cell and the mitochondria, greatly increasing its toxic effects on the latter [84].

This would be especially so for the salts and esters of glyphosate, which are more soluble than glyphosate technical acid (N-phosphonomethylglycine), which was used in Monsanto's chronic animal studies. It is interesting to note that the active principles actually used in Roundup glyphosate-based herbicide formulations in real-world applications are not solely the technical acid but rather the far more soluble salts and esters of glyphosate; i.e., potassium glyphosate, sodium glyphosate, ammonium glyphosate and the popular isopropylamine glyphosate. These formulations have been shown to be orders of magnitude more toxic than glyphosate in isolation [85].

COX catalyses the one-electron oxidation of four molecules of reduced cytochrome c and the four-electron reduction of oxygen to water. It is an essential component of the oxidative phosphorylation pathway in mitochondria that produces adenosine triphosphate (ATP), the "energy currency" of cells. Subunit II of COX contains a Cu_A redox centre, serves as a binding partner for cytochrome c, and as a participant in the electron transfer process [86]. Subunit II has a highly conserved glycine residue at the active site [87–89]. A mutant form of COX in *Rhodobacter sphaeroides* involving a substitution of valine for the conserved gly283 resulted in a complete block of access of oxygen to the active site [88]. Similarly, conversion of a conserved glycine in subunit II's active site to arginine in a yeast strain resulted in respiration deficiency [89]. A structural model of the redox center of subunit II includes *two* conserved glycines at positions 219 and 226, in close proximity to conserved amino acids that act as ligands to the Cu_A redox site and a glutamic acid residue implicated in cytochrome c binding, as schematized in Fig. 4 [90]. Obviously, substitution of glyphosate for glycine in either of these conserved sites would almost certainly harm enzyme function, leading to both impaired energy generation and oxidative damage. Glyphosate is also a strong chelator of copper, having a higher metal chelate formation constant—11.93—compared to its affinity for manganese (5.47), zinc (8.74) and calcium (3.25).

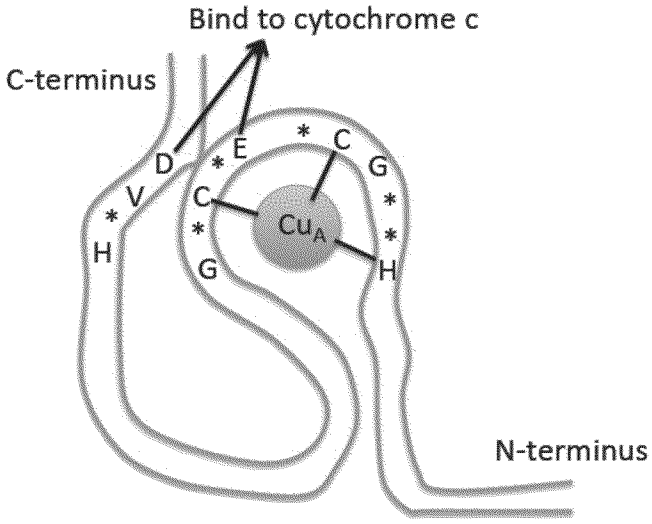

Figure 4. Schematic of structure of subunit II of cytochrome c oxidase (COX). Non-conserved amino acids are indicated by *. Adapted from Holm et al. (1987) [90].

4.6 Nrf2, KEAP1, fatty liver disease and bird beak deformities

Nrf2 is a leucine zipper protein that protects against oxidative damage due to an inflammatory response following various environmental triggers [91]. Interestingly, tumour cells often overexpress Nrf2, and this allows them to thrive in the face of severe oxidative stress [92–96]. High levels of Nrf2 activity cause chemotherapeutic resistance and correlate with a poor prognosis [94, 97].

Remarkably, although Nrf2 is cytoprotective, unregulated expression of Nrf2 is lethal in mice. Nrf2 is constitutively expressed, and KEAP1 is a cytoplasmic protein that regulates Nrf2 expression by binding to it to prevent its migration into the nucleus, thus enabling ubiquitination and subsequent degradation [98, 99]. Mice engineered to be KEAP1 deficient died postnatally, probably from malnutrition due to hyperkeratosis obstructing the oesophagus and forestomach [100]. The issue is that Nrf2 activates squamous epithelial cells to overproduce keratin, and a thickened oesophagus eventually becomes completely blocked.

KEAP1 maintains a cytoplasmic anchor through scaffolding with the cytoskeleton [98, 101]. The binding process depends upon a conserved region of the protein containing a sequence of two glycine residues (double glycine repeat, DGR). KEAP1 acts as a sensor for electrophilic and oxidative stresses to maintain an appropriate amount of Nrf2 activity. KEAP1 responds to oxidative stress through oxidation of sulfhydryl groups in conserved cysteine residues, and this causes it to release Nrf2, permitting its survival and entry into the nucleus, where it activates many phase 2 antioxidant defences

[102]. Unregulated overactivation of Nrf2 due to impaired KEAP1 function can be expected to lead to hyperkeratosis.

A newly emerging disease termed "avian keratin disorder" has become widespread among birds in certain regions of North America, particularly the interior of Alaska [103, 104], around the Great Lakes [105, 106], and off the coast of California (where agricultural runoff is a suspected factor) [107]. High rates of crossed beaks and other malformations were first noted around the Great Lakes in the mid-1970s [103, 105, 106], which is when glyphosate was first introduced into agricultural practice.

Chickadees are the most affected species, and they are known to frequent bird feeders supplying sunflower seeds, which according to the USDA are primarily grown in California, Colorado, the Dakotas, Kansas, Nebraska, Minnesota and Texas. Glyphosate is used in pre-planting, burndown, staging and preharvest dessication on sunflowers and specifically recommended to reduce crop loss due to feeding by wild blackbirds [108]. Frequent sightings of blackbirds with deformed beaks were first reported in 1979 [109].

A detailed study of potential toxic exposures to black-capped chickadees in Alaska, which investigated multiple toxic metals, organochlorine pesticides, polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDFs), was unable to identify any obvious exposure–disease relationship and, furthermore, the authors admitted that there was no known link between any of these chemicals and hyperkeratosis [104]. Notably, glyphosate was not studied. Avian keratin disorder is not present at birth, but rather develops over time and is most common among adult birds. Some physically examined birds revealed a systemic hyperkeratosis not limited to the beak. The most plausible explanation is that glyphosate substitutes for glycine in KEAP1, causing constitutive expression of Nrf2 leading to hyperkeratosis.

Non-alcoholic fatty liver disease (NAFL) has become an epidemic worldwide in recent years [110]. From 10 to 20% of patients with NAFL eventually develop non-alcoholic steatohepatitis (NASH), cirrhosis, end-stage liver disease, and hepatocellular carcinoma [111]. Mallory–Denk bodies (MDBs) are cytoplasmic inclusions associated with both alcoholic and non-alcoholic steatohepatitis [112]. These bodies are enriched in keratin, which is overexpressed through enhanced Nrf2 expression [111].

Non-melanoma skin cancer is the most common form of cancer among Caucasians [113]. Lankas and Hogan (1982) found sebaceous gland adenoma, and basosquamous cell tumour of the skin as well as fibrosarcoma, fibromas, neurofibrosarcoma, osteogenic sarcoma and mixed malignant tumour of the subcutaneous tissue associated with glyphosate residue ingestion by male rats during a 26-month study [59, 29]. Hyperkeratosis is a common feature of non-melanoma skin cancer [114]. Laryngeal keratosis is a risk factor for subsequent carcinoma [115]. Hyperkeratosis was observed in 2% of oesophageal biopsies performed on 1845 patients, and was linked to invasive squamous carcinoma of the oral cavity/larynx [116].

4.7 Tyrosine phosphatase and systemic inflammation

Glycine is a component of multiple sequence motifs that are consistent patterns within various groups of protein phosphatases. One sequence that includes a GXG subsequence is found in tyrosine phosphatases [117]. Another unique sequence containing two glycines is found in serine/threonine phosphatases [118]. Several acid phosphatases contain the conserved sequence, RHG [119]. A long signature motif found in a family of glucose-6-phosphatases, as well as several acid phosphatases and lipid phosphatases, contains a conserved glycine residue near the middle of the conserved sequence [120].

Protein tyrosine phosphatases are a class of enzymes that remove phosphate groups from phosphorylated tyrosine residues on proteins, and they generally have an anti-inflammatory rôle [121]. Tyrosine phosphatases play a very important rôle in the developing immune system, influencing the process of maturation of T-cells, as well as in the immune response in the adult [122]. Defective versions of a haematopoietically expressed cytoplasmic tyrosine phosphatase have been associated with multiple autoimmune diseases, including systemic lupus erythematosus, rheumatoid arthritis and type 1 diabetes [123–127]. T-cell protein tyrosine phosphatase (TCPTP), a negative regulator of JAK/STAT and multiple growth factor receptors, is highly expressed in haematopoietic tissues [128]. Defects in this gene have been linked to type 1 diabetes, rheumatoid arthritis and Crohn's disease through genome-wide association studies [124, 128, 129]. Substitution of proline or alanine for the conserved gly127 residue resulted in a 400-fold decrease in catalytic activity [130].

Studies on TCPTP-deficient mice have greatly enhanced our knowledge of this important protein [131–133, 128, 134, 135]. Homozygous TCPTP-deficient mice become ill and die by three to five weeks of age [131–133, 128]. They exhibit severe anaemia and infiltration of mononuclear cells into multiple tissues, along with a dramatic increase in expression of proinflammatory

cytokines systemically, including TNF-α, IFN-γ and IL-12 [133]. More specifically, inflammation of the synovial membrane and severe subchondral bone resorption of the knee were observed, along with significantly greater numbers of osteoclasts in the femur [123]. Heterozygous TCPTP-deficient mice respond with excess cytokine production and exaggerated gut inflammation to epithelial insults, inducing colitis [136].

Severe glyphosate-surfactant poisoning is manifested by gastroenteritis, respiratory disturbances, altered mental status, treatment-resistant hypotension, renal failure and shock [137]. The fatality rate ranges from 3 to 30%, and is mostly due to either pulmonary toxicity or renal failure. A case study from India specifically highlights pulmonary oedema following acute poisoning, along with a precipitous drop in blood pressure [138], probably due to loss of serum fluids into the abdominal and pleural cavities.

A paper from 1990 by Martinez et al. compared the effects of an oral dose of Roundup on rats to intratracheal installations [139]. The oral dose induced pulmonary oedema 6 h later, along with bloodstained weeping from the nose, diarrhoea, distended gastrointestinal (GI) tract, and ascites, suggestive of hypovolemic shock. The intratracheal instillations were much more toxic at much lower dose levels. A dose of 0.1 mg/animal caused 80% mortality, and 0.2 mg/animal gave 100% mortality. Pathological examination found haemorrhaging and congestion in the lungs.

Protein tyrosine phosphatase plays a crucial rôle in protection from pulmonary oedema by maintaining barrier function following an inflammatory episode [140, 141]. It is conceivable that, following an acute inflammatory response to glyphosate poisoning, glyphosate is taken up by cells and incorporated into newly synthesized tyrosine phosphatase, disabling its effectiveness. However, glyphosate would likely inhibit these phosphatases even in the absence of direct incorporation into the peptide chain. An investigation into 15 different synthetic compounds, all of which contained a phosphonyl group, demonstrated their effectiveness in inhibiting both tyrosine and serine–threonine phosphatases [142].

Chronic obstructive pulmonary disease (COPD) is the fourth largest cause of death in the USA. It has been linked directly to overexuberant kinase-based signaling cascades [143]. Enhanced kinase activity combined with impaired ability to turn off the signal through dephosphorylation, both of which can be explained by glyphosate interference, can easily account for such a pathology.

Monsanto's sealed documents filed with the US EPA for the registration of glyphosate technical acid show that glyphosate has adverse effects on the lungs of animals. We previously reported tumours found in the lungs of test animals [29]. The study authors also noted many non-neoplastic microscopic findings. In 1981, Lankas and Hogan reported that the more common findings were changes in the kidneys and lungs. The lungs of many of the rats had "changes associated with chronic respiratory disease such as the presence of peribronchial and perivascular mononuclear cells and foci of macrophages in alveoli." In addition, some of the physical symptoms included nasal discharge, excessive lacrimation and rales (abnormal crackling noises) caused by disease and congestion of the lungs. Tumours of lungs were also found and included reticulum cell sarcoma, malignant lymphoma, adenocarcinoma and carcinomas.

Monsanto's studies found that radiolabeled carbon in glyphosate was able to be recovered in the exhaled breath of rats [29]. *Pseudomonas aeruginosa* is among the very few microbial species that are known to be able to metabolize glyphosate and use it as a source of phosphorus [144]. *P. aeruginosa* infection has been linked to COPD [145]. Glyphosate is known to disrupt bacterial homeostasis leading to an overgrowth of resistant pathogens; it was found by the USGS to be present in the atmosphere [146]; thus inhalation of the compound (not just ingestion) would also harm the lung.

4.8 Hypothyroidism due to impaired thyroid-stimulating hormone activity

In [45], it was proposed that impaired activity of manganese-dependent protein phosphatase 1 (PP1) could explain a link between autism and maternal hypothyroidism, due to a dependency on PP1 for the pituitary to release thyroid-stimulating hormone (TSH). In that paper, it was argued that glyphosate chelation of manganese might severely decrease manganese bioavailability. This argument was supported by the extremely low serum levels of manganese found in dairy cows exposed to GM Roundup-Ready feed [147].

However, we have already seen that phosphatases contain conserved glycine motifs that are essential for their proper functioning. Another distinct possibility is that glyphosate substitutes for glycine directly in the conserved CAGYC region of the β-subunit of TSH itself. A rare mutation where the central glycine in CAGYC is replaced by arginine in an autosomally recessive trait results in cretinism (mental and growth retardation) [148]. This single mutation leads to the synthesis of a defective form of the β-subunit of TSH, which renders it unable to associate with an α-subunit. This results in severe systemic deficiency of TSH and hypothyroidism. It is plausible that a similar disruption of adrenal stimulation occurs because of glyphosate substitution for a conserved glycine in ACTH [149]. A homozygous

substitution of glycine by valine in codon 116 of ACTH resulted in a profile of seizures, hypoglycaemia, impaired immune function and respiratory distress, characterized as "ACTH resistance syndrome."

4.9 eNOS, sulfate and red blood cells

Endothelial nitric oxide synthase (eNOS), which resembles cytochrome P450, plays a crucial rôle in providing the signaling molecule, nitric oxide, in the vasculature [150]. NO induces smooth muscle cell relaxation in the artery wall, leading to improved vascular flow. eNOS is dynamically regulated at the transcriptional, post-transcriptional and post-translational levels. Much has been written about eNOS's "pathological" production of superoxide under certain conditions, especially when the cofactor tetrahydrobiopterin (BH4) is depleted [151, 152]. Regulatory control of eNOS is complex, and, in particular, it only produces NO when it is both phosphorylated and detached from its secured scaffold to caveolin in lipid rafts in the plasma membrane [153]. Caveolin-1 prevents calmodulin binding under low calcium conditions [154, 155] Excess calmodulin, produced in response to calcium signaling, triggers the release of eNOS from its caveolin-bound site [156], and subsequent phosphorylation enables NO production.

In [157, 158], it was proposed that eNOS is a "moonlighting enzyme" which, when membrane-bound, rather than being inactive, produces sulfate, catalysed by sunlight. The superoxide is drawn into a zinc-occupied cavity created by the eNOS dimer, where it oxidizes sulfane sulfur, bound to conserved cysteine residues [159, 160] that encircle the cavity, to produce free sulfate. Details can be found in [157].

Red blood cells (RBCs) contain significant levels of eNOS, which is permanently located just within the plasma membrane. This has presented a puzzle to researchers, and some have even suggested that it is residual, because NO would be rendered ineffective through binding with haemoglobin, which would also disrupt oxygen transport [157, 161]. RBCs also steadily produce cholesterol sulfate, which plays an important rôle in maintaining their membrane negative charge and protects them from lysis and aggregation [162, 163]. Insufficient cholesterol sulfate leads to a high rate of haemolysis and shortened life span. Thus, RBCs plausibly use their eNOS to produce sulfate, which is then conjugated with cholesterol and exported to the external membrane wall.

eNOS is a member of a class of NOS isoforms that includes inducible NOS (iNOS) and neuronal NOS (nNOS). All known members of this class contain a conserved glycine residue (gly450), including all mammalian NOSs as wall as avian and insect NOS enzymes [164]. Gly450 is essential for NOS dimerization. Conservative amino acid substitutions at gly450 of murine iNOS abolishes NO production, dimer formation, and BH4 binding to the enzyme [165]. Furthermore, eNOS uniquely (compared to iNOS and nNOS) contains a myristoyl group covalently attached to the conserved N-terminal glycine, gly2, which is essential for securing eNOS to the membrane [164, 166]. It has been proposed that the myristoylating enzyme has an absolute specificity for glycine [23]. Experiments in which the glycine was replaced by alanine showed that neither myristoylation nor palmitoylation took place, and thus the defective enzyme only appeared in the cytoplasm [167–170].

It should be noted that other enzymes also have a conserved N-terminal glycine that supports myristoylation, including cyclic AMP-dependent protein kinase [171], calcineurin B [172], neurocalcin [173] and NADH–cytochrome b5 reductase [174]. Neurocalcin is found mainly in retinal photoreceptors and in neurons, where it is involved in the transduction of calcium signals [175]. Neurocalcin binds to clathrin, tubulin and actin in the cytoskeleton via myristoylation, and this suggests it may play a rôle in moderating clathrin-coated vesicle traffic [176]. This rôle would be disrupted if glyphosate replaces glycine at the N-terminus.

Thus, it becomes apparent that, if glyphosate is substituted for glycine at either the gly2 or the gly450 sites, eNOS will malfunction in both of its rôles of producing either sulfate or nitric oxide. This will have widespread pathological effects related to excessive haemolysis (anaemia), insufficient supply of cholesterol sulfate to the tissues, and insufficient production of NO, leading to vascular constriction and hypertension. Disruption of iNOS function will lead to impaired immunity, since iNOS defends the host against infectious agents [177]. And, of course, other important enzymes that also support myristoylation via a terminal glycine will behave in unpredictable ways when that glycine is replaced with glyphosate.

4.10 Arylsulfatases

Arylsulfatases are a family of enzymes that remove sulfate from sulfated molecules. Substrates include: the sulfated glycosaminoglycans—keratin sulfate, chondroitin sulfate and heparan sulfate; the sulfated sterols—cholesterol sulfate, estrone sulfate, testosterone sulfate, DHEA sulfate etc.; sulfated phenolic compounds; and the sulfated lipids such as sulfatide (sulfated galactocebroside). A defective version of arylsulfatase A, which removes sulfate-21 from sulfatide, results in the

condition of metachromatic leukodystrophy [178]. The infantile form of this genetic disease is characterized by muscle wasting and weakness, muscle rigidity, developmental delays, blindness, convulsions, impaired swallowing, paralysis and dementia. Life expectancy is below five years.

All members of the arylsulfatase family are subject to a unique modification that is necessary for activation, involving the transformation of a cysteine residue into formylglycine (FGly) [179]. In a rare inherited disorder named multiple sulfatase deficiency (MSD), the activities of all sulfatases are severely reduced. This disorder involves an impairment in the transformation of cysteine to FGly. A highly conserved motif consisting of four amino acids (LTGR) is found in all human and microbial arylsulfatases, near the modified cysteine. A 16-mer segment including this motif is essential and sufficient for the formation of FGly [180]. It is likely that the conserved glycine residue in the motif is essential to support the flexibility needed to present the cysteine to the modifying enzyme [181]. Without this transformation, the enzyme is completely inactive. Therefore, displacement of this glycine by glyphosate would likely disrupt enzyme activation.

In a mouse model of autism, maternal immune activation through polyinosinic:polycytidylic acid (poly(I:C)) injection produced offspring with characteristic features of mouse autism [182]. Likely due in part to a leaky gut, these offspring had sharply elevated serum levels of 4-ethylphenylsulfate, produced by the gut microbes, with a 46-fold increase over controls. Injection of 4-ethylphenylsulfate into normal mice induced autistic behaviour. It is plausible that impaired phenol sulfatase activity, particularly in the context of a leaky gut, would cause the accumulation of sulfated phenols in the plasma, contributing to autism.

5. NEURODEGENERATIVE DISEASES

We have already seen that the pathology of Alzheimer's disease is linked to overexpression of GSK3, which can be induced by the substitution of negatively charged amino acids in place of glycine in the N-terminal region. Glyphosate is negatively charged at biological pH.

Beyond Alzheimer's, multiple neurodegenerative diseases are associated with aggregated and tangled proteins including Lewy bodies, tauopathies, senile plaques and neurofibrillary tangles. In this section, we will focus on four classes of neurodegeneration that can be linked to disruption of conserved glycines in specific misfolded proteins: prion diseases, Alzheimer's disease, Parkinson's disease and amyotrophic lateral sclerosis (ALS). In all four of these cases, it has been determined that rare soluble non-fibrillar forms of the aggregated proteins are much more damaging than the insoluble precipitates. It has also been shown that conserved glycines support the flexibility that is needed to allow the hydrophobic components of the molecule to assemble so as to precipitate out of aqueous solution. Glycine is hydrophobic, whereas glyphosate is amphiphilic, and it is also much bulkier than glycine. Glyphosate's solubility would likely be higher in the cytoplasm of a cell than in serum both because of the higher pH and because of cationic buffering by potassium. In fact, potassium salts are used in glyphosate formulations to increase its solubility. It seems plausible that the rare soluble non-fibrillar forms of aggregated proteins that are toxic have glyphosate in place of glycine in their structure.

5.1 Prion diseases

Prion diseases, also called transmissible spongiform encephalopathies, are novel degenerative diseases in which the infective agent is a misfolded protein. Prions are believed to be responsible for Kuru, Creutzfeldt-Jakob disease, and bovine spongiform encephalopathy (BSE, mad cow disease). BSE first appeared in the United Kingdom in 1986, after glyphosate had been used to control weeds in animal feed for at least a decade. While BSE is believed to be caused by feed contaminated with the brain, spinal cord or digestive tract of infected carcasses, there remains the open question of what caused the original appearance of misfolded proteins to initiate the infection. Prion proteins contain a glycine-rich hydrophobic region that shows almost perfect conservation across a wide range of species. This region appears to be important for the misfolding process and prion propagation [183]. It seems remarkable that a highly conserved region of the protein, unaltered by genetic mutations, could be the source of the toxicity. The normal form of prion proteins, PrP^{C}, is rapidly catabolized, whereas a pathogenic isoform, PrP^{Sc}, is highly resistant to proteolysis [184]. A subsequence containing only PrP 106–126 is a highly conserved unstructured region of PrP, which is considered to be the main contributor to fibrillogenicity. It has a high tendency to aggregate into a β-sheet structure forming amyloid fibrils *in vitro* [185, 186].

There is controversy regarding whether the toxicity is due mainly to mature fibrils or to protofibrillar aggregates. A definitive study [187] showed that two strictly conserved glycine residues, at positions 114 and 119, within the highly conserved region, are the main drivers behind fibril formation, likely due to the high flexibility that they introduce in the molecular structure. If either of these is substituted by glyphosate, fibril formation would be impaired, due to the decreased flexibility. Remarkably, although replacement of these

glycines with alanine interfered with aggregate formation, it produced a higher concentration of a soluble non-fibrillar form which was, however, extremely neurotoxic [184]. Alanine has an additional methyl group, which makes it a bulkier molecule than glycine, restricting flexibility of the assembled protein. Glyphosate substitution for glycine would be expected to be even more disruptive than alanine, given its additional methylphosphonyl group. The lack of flexibility to organize the hydrophobic unit into a fibril will favour the toxic soluble form of the peptide. Furthermore, glyphosate can be expected to resist enzymatic degradation, and glyphosate-containing peptoids would also be resistant to proteolysis, in both cases due mainly to the highly stable C–P bond [188].

5.2 Alzheimer's disease, prions and β-amyloid

Alzheimer's disease is the most common form of dementia, accounting for 60% to 80% of all cases [189]. Worldwide, the prevalence of dementia was more than 35 million in 2010, and projected to be more than 65 million by 2030 and 115 million by 2050 [190]. The incidence of Alzheimer's disease is increasing at an alarming rate in the United States, in step with the dramatic rise in the use of glyphosate on corn, soy and wheat crops [30]. β-amyloid (Aβ) is now well established as a causal factor in Alzheimer's disease, although the mechanism of toxicity remains controversial [191]. The Aβ that accumulates in the Alzheimer's brain consists of deposited insoluble fibrillar components, monomers, and soluble oligomers, the latter being the most toxic form. The levels of the monomer and the deposited precipitates are orders of magnitude greater than the levels of the toxic soluble oligomers, which are known to cause both acute synaptotoxicity and neurodegeneration [190]. The pharmaceutical industry has developed immunotherapies that target Aβ, but none of them are specific to the toxic soluble form, and this likely explains their lack of efficacy [192]. The challenge to the industry is to develop a drug that uniquely targets the soluble oligomers.

Growing evidence supports the concept that soluble non-fibrillar forms of Aβ are the most toxic, and their toxicity can be mimicked by a synthetic peptide containing the first 42 residues (Aβ42) [193]. Interestingly, Aβ has a GXXXG domain with conserved glycines at positions G29 and G33 [194]. Substitution of alanine in place of glycine at residues G29 and/or G33 led to an attenuation of dimerization, and specifically increased the formation of Aβ38 and shorter species at the expense of Aβ42. Munter et al. argued that the glycines promote dimerization and that this impedes access of proteases to the molecule, resulting in the survival of the longer peptide chain. However, it is extremely unlikely that a highly conserved element in the protein could be responsible for disease. An alternative thought is that glyphosate substitutes for glycine, increasing solubility and preventing proteolysis. This is in line with work that has shown that aminopeptidases can be disrupted by methylphosphonic acid [10]. It can be envisioned that the presence of glyphosate in place of glycine upstream interferes with the stripping off of residues 41 and 42 by γ-secretase, leaving behind a soluble and damaging Aβ42 peptide.

Magnesium deficiency has been linked to Alzheimer's disease [195, 196], and *in vitro* studies have shown that low magnesium leads to increased production of Aβ [197]. Glyphosate's chelation of +2 cations can be expected to deplete magnesium availability, and studies on soy have shown that glyphosate interferes with magnesium uptake in plants [198, 199]. The effect of low magnesium will work synergistically with glyphosate's inclusion in the Aβ peptide to induce Alzheimer's disease (AD).

Bush, Cherny and others note that zinc, copper and iron accumulate in brain plaques [200–204]. Aβ is a Zn and Cu metalloprotein, and zinc has been shown to induce amyloid formation in Aβ [200]. Glyphosate strongly chelates Cu, as well as Zn, and ferrous iron, Fe^{2+}, which, as Monsanto's John E. Franz notes, quickly oxidizes to the ferric form, Fe^{3+}. Metal chelate formation constants show strong binding potential for these elements at 11.9, 18.2 and 6.9 for Cu, Zn and Fe respectively, as compared to the parent amino acid glycine at 8.6, 5.4 and 4.3 respectively. Maynard et al. (2005) assert: "Aβ and APP (amyloid precursor protein) expression have both been shown to decrease brain copper (Cu) levels, whereas increasing brain Cu availability results in decreased levels of Aβ and amyloid plaque formation in transgenic mice. ... Interestingly, the highest levels of free or synaptic Zn are found in cortex and hippocampus, the regions most affected in AD. Zn^{2+} reuptake after synaptic release is a rapid, energy-dependent process. Hence, energy depletion could cause a pooling of extracellular Zn^{2+}, contributing to Aβ deposition" [203]. Glyphosate's disruption of COX could impair energy supplies, leading to excess Zn^{2+} accumulation. Religa et al. show that zinc levels rise with tissue amyloid levels and "were significantly elevated in the most severely demented cases (CDR 4 to 5) and in cases that had an amyloid burden greater than 8 plaques/mm^2. Levels of other metals did not differ between groups." They concluded that the zinc accumulation is dominant in cases of advanced Alzheimer's disease and linked to brain amyloid peptide accumulation as well as to the severity of the disease [204]. Such a pairing of these elements with the amino acid glyphosate in amyloid protein would likely

form misfolded proteins as well as insoluble plaques due to the known resistance of the analogue to proteolysis.

Because of its small ionic radius and strong positive charges, aluminum firmly binds to metal-binding and phosphorylated amino acids, acting as a cross-linker by binding multiple amino acids simultaneously [205], which can cause the oligomerization of proteins, inhibiting their degradation by proteases. This is believed to be a mechanism for the neurofibrillary pathology of phosphorylated tau protein [206, 207]. We have already established that glyphosate likely induces excess protein phosphorylation due to its excitatory effects on kinases and inhibitory effect on phosphatases. However, glyphosate itself also binds aluminum, particularly through oligomeric complexation of an aluminum ion [208]. Thus, two molecules of a peptoid/peptide, both of which contain glyphosate, will likely become linked together via an aluminum ligand binding two embedded glyphosate residues, one in each peptide. This would almost surely lead to impaired protein degradation and accumulation of fibrils. *In vitro* studies have shown that soluble dimeric and oligomeric forms of Aβ are more toxic than monomeric Aβ [209, 210].

Increasingly, prions are suspected of playing a rôle in Alzheimer's disease. A recent, well-designed study has demonstrated that a triad formed from amyloid-β, PrP^C and a metabolic glutamate receptor is critical for the disruption of synaptic plasticity by the soluble non-fibrillar forms of Aβ [211]. High affinity binding of Aβ to PrP has been localized to the region of PrP from residue 91 to residue 119 [212]; within this region, residues 114 and 119 are the two conserved glycines in PrP [184].

5.3 Cataracts and Alzheimer's disease

Crystallin is the dominant protein found in the lens of the eye. Cataract formation is the result of amyloid protein aggregation from crystallins, which results in insoluble β-amyloid deposits in the lens [213]. Post-mortem studies on Alzheimer's patients revealed that Aβ is also present in the cytosol of cells from the lenses of people with Alzheimer's disease and that it is associated with cataracts [214]. In fact, amyloid plaques in cataracts and in the brain in Alzheimer's patients were identical. Furthermore, α-B-crystallin is found in association with brain plaques and fibrillary tangles in Alzheimer's, Creutzfeldt-Jakob and Parkinson's diseases.

An increase in phosphorylation of crystallin is linked to increased cataract risk [215]. Such an increase can be expected in the context of hyperactive kinases and inhibited phosphatases, such as is expected with glyphosate insertion in place of glycine in these molecules. Furthermore, a single mutation of the conserved glycine-98 residue of crystallin to arginine results in a defective form of the protein that lacks chaperone function, and is susceptible to heat-induced aggregation [216]. This mutation is also linked to increased risk of cataracts. The α-crystallins in particular play an important rôle in chaperoning crystallins to prevent protein aggregation and precipitation. Thus, it appears that alterations to glycine residues can play a rôle in cataracts that is completely analogous to the rôle they play in Alzheimer's disease, and the two conditions are closely linked.

Perhaps unsurprisingly, given these cataract risk factors linked to defective crystallin, Monsanto's own early rodent studies found a link between glyphosate exposure and cataract formation [29]. Monsanto's 1990 (Stout & Ruecker) chronic rat exposure study found significant incidence of y-sutures and other ophthalmic degenerative lens changes caused by glyphosate. The pathologist for the study, Dr Lionel Rubin, noted in his ophthalmoscopic examination report that: "There appears to be a dose-related occurrence of cataract affecting male group M3. The type of cataract affecting this group is the diffuse posterior sub-capsular type and to a lesser extent, anterior polar and sutural types." Displacement of pupils and ocular opacities in the presence of glyphosate was also noted in 1983 by Knezevich and Hogan [29].

5.4 α-Synuclein and Parkinson's disease

A 35-amino-acid peptide was isolated from the insoluble core of Alzheimer's disease amyloid plaque, and was found to be a fragment of α-synuclein, a neuronal protein of unknown function. This fragment had a striking sequence similarity with the carboxyl terminal of Aβ, as well as a region of PrP implicated in amyloid formation [217]. α-synuclein aggregates are found in association with Lewy bodies present in Parkinson's disease patients, and is also linked to dementia and multiple system atrophy [218, 219]. A novel ELISA test has been developed that detects only oligomeric soluble aggregates of α-synuclein in the blood. It was shown that 52% of Parkinson's disease patients tested positive as against only 15% of controls [220]. A 9-residue sequence, ^{66}VGGAVVTGV^{74}, containing three glycine residues, has been shown to be crucial for the fibrillization and cytotoxicity of α-synuclein [221]. Fibrillization and cell toxicity are completely eliminated when this sequence is deleted.

5.5 TDP-43 and ALS

Transactive response DNA binding protein 43 (TDP-43) is a transcriptional repressor that binds both DNA and RNA, and has multiple other functions, including pre-

mRNA splicing and translational regulation. Exon 6 of TDP-43 encodes a C-terminal glycine-rich domain where multiple missense mutations have been implicated in association with amyotrophic lateral sclerosis (ALS) and frontotemporal lobar degeneration (FTLD), a subtype of dementia [222]. TDP-43 is now considered to be the signature class of inclusional lesions for sporadic ALS. TDP-43 is also recognized for its ability to repress HIV transcription [223].

The C-terminus of TDP-43 bears sequence similarity to prion proteins. Synthetic peptides near residue 315 form amyloid fibrils *in vitro* and cause cultured neuronal death [224]. Accumulation of protease-resistant fragments may spread the disease phenotype among neighbouring neurons, similar to the pathology associated with prion diseases.

TDP-43 is a member of a class of ribonucleoproteins known as 2XRBD-Gly proteins. The class share the common feature of a glycine-rich C-terminus that probably serves a similar function in all the members of the class. Among 53 unrelated sporadic or familiar ALS cases, two of whom suffered from concurrent FTLD, 29 different missense mutations in TDP-43 have been reported [222]. All but one of them occurred in the C-terminal glycine-rich domain of exon 6. The subset of these mutations that involve a substitution for glycine are concentrated in the region between residue 275 and 310, the most glycine-dense region of the C-terminus. Thus, replacing glycine with any other amino acid increases risk to ALS. Non-genetic replacement with glyphosate can be expected to have a similar outcome.

About 20% of patients with familial ALS have mutations in Cu,Zn superoxide dismutase (SOD). One of the more common mutations found is a substitution of alanine in place of glycine at gly93, which introduces a modest gain of function [225]. Although this change appears to have little effect on enzyme activity, transgenic mice with this genetic mutation become paralysed in one or more limbs as a result of motor neuron loss in the spinal cord and do not live beyond five or six months. Clearly, substitution of a bulkier molecule in place of glycine disrupts the function of the enzyme in ways that are not yet understood.

6. MICROBIOME DISRUPTION AND IMMUNE SYSTEM IMPAIRMENT

In this section we discuss several examples of proteins that play a rôle either in maintaining the health of the gut microbiome or in human defence against microbial infection. In each case, conserved glycines are essential for protein function. We begin with a section on the disruption by glyphosate of PEP carboxylase, which has major impact on microbial health, as this enzyme is central to both carbon fixation and nitrogen fixation. The next section describes glycine riboswitches and their rôle in the metabolization of glycine in the medium via the glycine cleavage system. This is important both to detoxify glycine and to supply methyl groups for one-carbon metabolism. Antimicrobial peptides such as α-defensin are important for human immune function, and these proteins contain conserved glycines. Finally, HIV-AIDS infection is linked to impaired phosphatase activity, particularly a constitutively expressed tyrosine phosphatase that is highly expressed in T-cells.

6.1 Nitrogen fixation and PEP carboxylase

Mung beans exposed to glyphosate at levels appropriate for weed control show reduced fixation of nitrogen into organic matter [226]. Nitrogenase, an essential enzyme in plants for nitrogen fixation, converts nitrogen gas to ammonia, which is then conjugated with glutamate to produce glutamine. A study on lupins showed that glyphosate exposure, even at sublethal levels, severely inhibited nitrogenase activity, resulting in a decrease in starch content and an increase in sucrose content. The practice of using glyphosate as a pre-harvest ripener in sugar cane to increase yield exploits this property of increased sucrose production [227]. The mechanism was traced to inhibition of phosphoenol pyruvate carboxylase (PEPC), subsequent to accumulation of shikimate via blockage of the shikimate pathway [228]. PEPC plays an essential rôle in the incorporation of both CO_2 and nitrogen into plants [229, 230].

PEPC's regulation is controlled by levels of shikimate rather than through product inhibition. Since PEP is the input to both PEPC and 5-enolpyruvylshikimic-3-phosphate synthase (EPSPS), the step in the shikimate pathway that glyphosate disrupts, PEP accumulates at ever greater levels while both the carboxylase pathway and the shikimate pathway are blocked. Most of the carbohydrate pool is then exhausted through conversion to shikimate, acting as a metabolic sink. Shikimate accumulates to very high levels due to glyphosate's inhibition of EPSPS, while the synthesis of aromatic amino acids, normally derived from shikimate, is blocked.

At the extreme C-terminus of PEPC there is an invariant glycine residue which plays an essential rôle in enzyme activity [231]. Even the conservative replacement with alanine (one extra methyl group) leads to loss of function both *in vivo* and *in vitro*, with an experimentally demonstrated drop to only 23% of the wild type activity level in sorghum [231]. In experiments on *E. coli*, perturbation of the terminal gly-961 by either

conservative neutral substitution with alanine or valine or even by specific deletion did not seem to cause any apparent harmful effects. However, replacement with a negatively charged amino acid such as aspartate resulted in a complete shutdown of enzyme activity. The authors wrote: "PEPC appears to not tolerate additional negative charge at its extreme C-terminus beyond that of the main chain free CO_2^- group."

Glyphosate substitution would of course represent the introduction of additional negative charge. Thus, it seems almost certain that glyphosate substitution for glycine at this conserved terminal site would severely inhibit the enzyme's activity, beyond any inhibition already induced by the build-up of shikimate. This offers a further explanation for the empirically observed suppression of PEPC by glyphosate, and it also suggests that glyphosate disrupts nitrogen fixation [232].

6.2 Glycine riboswitches

Glycine is both essential and toxic to bacteria. It is well known that glycine inhibits bacterial growth [233–236], by substituting for alanine into peptidoglycan precursors [237–239]. Glycine-containing precursors are poor substrates for peptidoglycan biosynthesis enzymes as well as for the transpeptidation reaction, leading to both a deficiency in muropeptides and a high percentage of muropeptides that are not cross-linked. These modifications to the cell wall severely restrict growth.

As a consequence of glycine's toxicity, it is important for bacteria to be able to quickly break glycine down into basic building blocks. Oxidative cleavage to CO_2, NH_4^+ and a methyl group is carried out by the glycine cleavage system (GCS), and the methyl group becomes a major source for one-carbon metabolism, beginning with the conversion of tetrahydrofolate (THF) to methylene-THF [237], which is then used to biosynthesize various cellular compounds, including, importantly, purines and methionine. The GCS also produces NADH in the oxidative cleavage step, which yields energy through the electron transport system. As well the GCS is the most prominent pathway for serine and glycine catabolism in humans [240]. Mutations in GCS-encoding genes are linked to defects in neural tube development, causing spina bifida and anencephaly [241, 242, 243].

Riboswitches are small non-coding RNA segments typically located in the 5' untranslated regions (UTRs) of bacterial mRNAs, and they serve as both sensors of cellular metabolites and effectors of regulatory responses. Studies have revealed the presence of glycine riboswitches in the 5' UTRs of the enzymes involved in the GCS [244]. These riboswitches bind directly to glycine and turn on the genes for transcription of enzymes needed to metabolize it. In this way, glycine is quickly cleared and put to good use, fueling the electron transport chain and the one-carbon metabolism pathways. Glycine is highly toxic to mutants missing these riboswitch regions; a medium containing only 1% glycine severely restricts their growth [237].

Glyphosate is a patented antimicrobial agent, and its toxicity to humans has been attributed in part to its adverse effect on the microbiome [26]. In addition to other actions such as metal chelation and inhibition of the shikimate pathway, glyphosate, acting as a glycine analogue, disrupts the glycine regulatory system and cell wall construction. Glyphosate perhaps, like glycine, substitutes for alanine in the peptidoglycans. Glyphosate likely also binds to the glycine riboswitches, acting as a glycine analogue, and it could interfere with the signaling mechanism due to its altered structure and negative charge.

6.3 α-Defensin and antimicrobial peptides

Human α-defensins are important members of a broad class of antimicrobial peptides that are found throughout the tree of life [245, 246]. All of the human α-defensins, although their molecular structures are quite variable, contain a conserved glycine, gly17, which is part of a β-bulge structure. Gly17 is in fact the only non-cysteine residue that is invariant in α-defensins. Gly17 is part of a larger structural motif known as the γ-core, which is present across many classes of antimicrobial peptides. When other amino acids are substituted for gly17, dimerization is impaired, and this disrupts the ability to self-associate, inhibit anthrax lethal factor, and kill bacteria [247].

Even the conservative substitution of L-alanine for glycine inhibits protein function. Bulkier hydrophobic side chains are likely to create steric clashes, a polar side chain might introduce hydrogen bonds, and a charged side chain might invite electrostatic attraction or repulsion [247]. Thus the methylphosphonyl group in glyphosate in place of the conserved glycine is likely to have a major negative impact on the protein's effectiveness against microbes.

6.4 HIV-AIDS

Protein tyrosine kinases (PTKs), acting in concert with protein tyrosine phosphatases (PTPases), control levels of cellular protein tyrosine phosphorylation. Changes in tyrosine kinase and phosphatase activity are implicated in numerous human diseases, including cancer, diabetes and pathogen infectivity [248].

Impaired phosphatase activity due to disruption of a conserved glycine may play a rôle in increasing HIV infectivity. c-Jun N-terminal kinases (JNKs) are signaling

kinases that respond to mitogen-activated protein (MAP) kinase signaling and regulate many cellular activities. JNKs are activated through dual phosphorylation of threonine and tyrosine residues, and inactivated by matched phosphatases [249]. JNK activation is implicated in HIV infections. Quiescent (resting) human peripheral blood T lymphocytes do not support efficient HIV infection, both because reverse transcription takes longer and because of impaired integration of the viral complementary DNA [250]. Cellular JNK is only expressed following activation, and it regulates permissiveness to HIV-1 infection. In JNK-activated T lymphocytes, viral integrase is phosphorylated by JNK on a highly conserved serine residue in its core domain. This modification is required for efficient HIV-1 integration and infection. As a consequence, it is mainly the activated lymphocytes that are infected.

A dual-specificity PTK that can also dephosphorylate threonine/serine residues is human tyrosine phosphatase vaccinia H1-related (VHR). This phosphatase has special significance because it is highly expressed in T-cells, and it is expressed constitutively rather than in response to a signaling cascade [130]. VHR has a conserved glycine residue within the protein tyrosine phosphatase (PTP) loop, which maintains its flexibility and is essential for substrate binding and enzymatic activity [251]. Substitution of either proline or alanine for the conserved G127 residue resulted in mutants with a decrease in catalytic activity of about 400-fold, and the K_i value was increased by 38-fold with alanine and 19-fold with proline [130].

VHR may play a significant rôle in protection from HIV infection due to its constitutive expression in T-cells [252]. VHR is a negative regulator of the Erk and JNK pathways in T-cells. Only constitutively expressed enzymes are present in the early phase immediately following MAP kinase activation. VHR is the only known MAP kinase-specific phosphatase that is constitutively expressed in lymphocytes. It can thus immediately dephosphorylate activated JNK and in this way protect from HIV infection.

It is likely that glyphosate's disruption of VHR and other protein phosphatases with conserved glycines has implications far beyond HIV infection, since protein phosphorylation status plays such an important rôle in signaling cascades. In fact, the combination of activation of kinases and suppression of phosphatases that can plausibly be induced through glyphosate's displacement of conserved glycines in the enzymes can be predicted to lead to an overabundance of phosphorylated molecules, systemically. This may contribute to the recent antiphospholipid syndrome epidemic. It may also play a rôle in cancer: tyrosine kinase inhibitors are often used to treat cancers with aberrant tyrosine kinase receptor activity [253].

7. EFFECTS ON SPECIFIC ORGANS

In this section we examine proteins with conserved glycines, where substitution with glyphosate can explain porphyrias and liver disease, renal failure due to impaired iron uptake (leading to simultaneous iron toxicity and iron deficiency), disruption of cytochrome P450 enzymes and glaucoma, impaired collagen function leading to osteoporosis and increased risk to bone fracture, and malignancy in non-Hodgkin's lymphoma due to defective binding of tumour cells to dendritic cells.

7.1 Porphyrias and liver disease

Gly232 is a strictly conserved residue in the enzyme protoporphyrinogen oxidase (PPOX). A paper from 1997 discussed three patients with a missense point mutation substituting arginine in place of this glycine residue. This led to a deficiency in PPOX activity, resulting in impaired haem synthesis and variegate porphyria [254].

In a mouse model of porphyria, it was shown that mice developed fatty liver disease due to the accumulation of protoporphyrin in the liver and resulting induction of oxidative stress. The model involved excessive inhibition of KEAP1-mediated Nrf2 degradation, resulting in upregulation of the expression of keratin and the appearance of keratin-rich Mallory–Denk bodies [111].

It seems possible that, in humans, glyphosate substitution for glycine in PPOX would lead to a non-genetic expression of porphyria, and glyphosate substitution for glycine in KEAP1 would interfere with KEAP1's ability to suppress the overexpression of Nrf2. This model would explain protoporphyrin-induced fatty liver disease in the context of glyphosate exposure, progressing to cholelithiasis, end-stage liver disease and liver failure [255].

7.2 Siderophores and renal failure

Siderophores are small iron-chelating compounds secreted by microörganisms as a mechanism to solubilize insoluble ferric iron compounds [256]. The class of enzymes that imports these siderophores is important both for iron uptake and for uptake of vitamin B_{12}. These enzymes contain two conserved glycines, and these are the only invariant residues found in every enzyme in this family of iron transport proteins [257]. Substitution of alanine for glycine was better tolerated than substitution of larger amino acids. This suggests that glyphosate substitution would induce impaired iron uptake as well as impaired vitamin B_{12} uptake in *E. coli* and other microbes.

In *Bacillus subtilis*, an important microbe in the human micriobiome, iron deprivation induces upregulation of all the enzymes involved in the synthesis of the iron siderophore, bacillibactin [258], including the enzymes needed to synthesize glycine, a precursor to bacillibactin. Glyphosate has been shown to inhibit growth in tumour cells, and the proposed mechanism was inhibition of glycine synthesis from serine, through its action as a glycine analogue [17]. Thus, it can be expected that both siderophore synthesis and iron-loaded siderophore uptake will be impaired in the presence of glyphosate. Glyphosate also chelates iron, making it unavailable.

In our previous work [29] we discussed details of a Monsanto study by Lankas and Hogan (1981), which found microscopic changes of the kidney associated with chronic progressive nephropathy. Focal tubular hyperplasia and focal tubular dilation, which precede acute tubular necrosis and nephrosis, were detailed. Acute tubular necrosis (ATN) is a life-threatening syndrome caused by impaired function of the proximal tubule of the kidney [259–261]. This is the form of kidney failure that characterizes the alarming epidemic of kidney disease among agricultural workers in Sri Lanka and elsewhere, which has been linked to glyphosate working synergistically with toxic metals [262]. It has been found through experiments in mice that defective iron uptake from siderophores in the proximal renal tubule can cause simultaneous iron deficiency and iron toxicity, explaining the disease process [263]. Unbound iron forms reactive ferryl or perferryl species [264] which can damage lipids, nucleotides and the DNA backbone [265, 266]. Remarkably, Mori et al. [263] showed that the proximal tubules markedly upregulate synthesis of lipocalin, a protein that specifically functions to take up microbial siderophores bound to iron, under stress conditions. In fact, the tubules appear to rely on microbial siderophores to supply their iron. A GXW motif is conserved in all members of the lipocalin family [267]. Hence, it can be expected that impaired siderophore synthesis by microbes, combined with impaired uptake in the renal tubules due to glyphosate substituting for conserved glycines in lipocalin, can lead to destructive oxidative damage by free iron paradoxically combined with iron deficiency. Because several enzymes involved in amino acid biosynthesis are iron-dependent, iron deficiency causes amino acid starvation [258], further stressing the renal tubules.

Transferrin-based iron uptake is likely to also be disrupted by glyphosate, and this can help explain the worldwide iron deficiency anemia epidemic, linked to both impaired brain development [268] and obesity [269]. A recent study investigated the rôle of the conserved sequence of four glycines in the protein responsible for uptake of iron from *human transferrin* in the infective agent, *Neisseria gonorrhoeae* [270]. The four glycines follow a hydrophobic lipid anchor region that secures the molecule in the membrane. While deletion of the glycines did not prevent anchoring in the membrane, it did interfere with the uptake of iron from transferrin, suggesting impairment of the flexibility needed to form the iron chamber, which allows for efficient iron internalization through the β-barrel. It can be anticipated that this protein and others similarly designed in other species, concerned with mineral uptake, would be impaired by glyphosate substitution for conserved glycines.[1]

7.3 Cytochrome P450 enzymes and glaucoma

Studies on rats have shown that glyphosate suppresses the activity of cytochrome P450 enzymes (CYPs) in the liver [26, 273]. In a hinge region of CYP1B1, characteristic of microsomal CYPs, a proline- and glycine-rich region follows the N-terminal transmembrane domain. It has been proposed that the proline-proline-glycine-proline motif joins the membrane-binding N-terminus to the globular region of the P450 protein [274]. The hinge permits flexibility between the membrane-spanning domain and the cytoplasmic portion of the molecule [275]. Mutations in the hinge regions interfere with the proper folding and haem-binding of CYPs [275, 276].

Mutations in CYP1B1 have been closely linked to primary congenital glaucoma [277, 278]. In a study involving 24 Saudi Arabian families, the most common mutation was a G → A transformation at nucleotide 3987, occurring in 78% of the chromosomes analysed [277]. This results in substitution of glutamate for gly61 in the hinge region. Gly61 is one of the most highly conserved residues in this region.

Another study involving five families with primary congenital glaucoma in Saudi Arabia identified 2 out of 8 missense mutations that involved glycine being replaced by another amino acid, one being the gly61 glu mutation [278]. The second mutation involved a substitution of tryptophan for glycine in helix J in the 5' end of exon 3, part of the core structure of the enzyme. Both mutations were associated exclusively with the glaucoma phenotypic expression. It is possible that glyphosate substitution for glycine at these two conserved residues contributes to

[1] A pattern of glycine-rich regions near hydrophobic sequences occurs repeatedly in protein design, and is probably necessary for flexibility near the membrane anchor region [271, 272].

glyphosate's observed suppression of CYP enzyme activity, more generally.

7.4 Collagen, bone fractures and osteoporosis

Glycine is the most common amino acid in collagen, making up one third of the total amino acid residues in the molecule. Over 10% of the molecule consists of a helical region, where each coil in the triple helix is made up of glycine-led triplets of the form $(gly\text{-}2\text{-}3)_n$ [279]. Proline and hydroxyproline are also highly overrepresented in collagen, and they appear in over half of the glycine-led triplets. Triple helix formation is essential for the transport of type I procollagen out of the ER for secretion to form extracellular matrix fibrils to support mineral deposition in bone [280].

Osteogenesis imperfecta (OI), which is also known as brittle bone disease, is a congenital bone disorder characterized by a strong predisposition towards bone fractures. The condition is caused by genetic mutations in collagen, mainly collagen I. Overwhelmingly, these mutations concern substitutions for glycine in the glycine triplet regions [281–283]. One third of the glycine mutations that occur in the alpha chain of collagen 1 are lethal, especially when the substituting amino acid is electrostatically charged or has a side branch [284]. The lethal regions align with proteoglycan binding sites, suggesting impaired proteoglycan attachment. The majority of the substitutions involve glycine residues in the triple helical domain. Mutations have been found that account for all of the possible amino acid substitutions for glycine, except the stop codon, that can be produced by changing just one nucleotide in the DNA code for glycine.

A case of a male child in which glycine was replaced by tryptophan (the only case known for this substitution) in a residue on the α2 chain demonstrated a severe phenotype characterized by numerous fractures already present at birth, and numerous additional fractures occurring postnatally. By the age of 9 years his height was below the 3rd percentile, he suffered from generalized osteoporosis, and had a large skull, thin ribs, a severely deformed pelvis, and markedly deformed long bones [283]. It is thus likely that random replacements of any of the multiple glycine molecules in collagen with glyphosate would also disrupt collagen's structure, leading to osteoporosis as well as a sensitivity to bone fractures, which might in part explain "shaken baby syndrome" [285]. Osteoporosis is also a modern epidemic [286]: As of 2003, osteoporosis affected one in three women and one in twelve men worldwide [287]. We are witnessing an increase in age-specific fracture rates due to an unknown aetiology.

7.5 Non-Hodgkin's lymphoma

Non-Hodgkin's lymphoma (NHL) has been linked to glyphosate in occupational exposure studies [288, 289]. The tumour cells of NHL patients appear to be neoplastic versions of activated B cells, in that they both express very late antigen-4 (VLA-4), which binds to vascular cell adhesion molecule-I (VCAM-1) expressed on follicular dendritic cells, and in this way traps the dendritic cells. This binding mechanism is central to the generation of the immune response, and it influences activation and proliferation of immune cells. Blocking studies demonstrated that the binding of follicular lymphoma cells to malignant follicles was inhibited with anti-VLA-4 and anti-VCAM-1 antibodies [290]. The VLA-4 from malignant cells studied from different patient populations demonstrated variable and weakened ability to bind to VCAM-1, and it was proposed that defective binding might be the factor that induces malignancy. The authors suggested that lower adhesive capacity might explain the tendency of neoplastic cells to disperse: "Therefore, a deregulated or dysfunctional VLA-4:VCAM-1 interaction in follicular NHL may be similarly important to the proliferation of the neoplastic cells" [290].

VLA-4 is required for normal development of both T- and B-cells in the bone marrow, in part by regulating the balance between proliferation and differentiation of haematopoietic progenitors [291]. It can therefore be expected that impaired function would lead to pathologies such as immune dysfunction and cancer. Two conserved glycine residues at positions 130 and 190 are essential for its adhesive activity [292]. Glyphosate's link to NHL may therefore be explained through substitution of glyphosate for glycine at one or both of these conserved residues.

8. NEURAL TUBE DEFECTS AND AUTISM

Glyphosate can penetrate past the placenta [293]. Alarming increases in birth defects such as microcephaly, anencephaly, cleft palates and other facial defects have been found in regions of South America and Paraguay where glyphosate is used extensively on core crops [294, 295]. The US Centers for Disease Control have reported on an excessive number of anencephaly births in Yakima (Washington), at four times the national average rate [296]. This increase coincided with a large increase in the use of glyphosate to control waterway weeds.

A recent study by Roy et al. on zebrafish embryos revealed that glyphosate causes microcephaly in zebrafish, and that the forebrain and midbrain are affected (but the hindbrain was spared) [297]. A US-based study found that the cerebellum is frequently disproportionately large in human microcephaly,

particularly in the more severe cases, reflecting a larger effect on the forebrain compared to the hindbrain [298].

A study on tadpoles conducted by Carrasco et al. involved dilutions of 1/500,000 of glyphosate formulations. [299]. They showed several pathologies in development that relate to neural tube defects, including a reduction in head size, cyclopia, reduction of the neural crest territory at neurula stages, and craniofacial malformations. They suggested excess retinoic acid as the mechanism of toxicity. However, we suspect that both impaired DNA repair mechanisms and impaired folate one-carbon metabolism (FOCM) may also play a rôle.

Polynucleotide kinase 3-phosphatase (PNKP) plays an important rôle in DNA repair. As its name implies, it is both a phosphatase and a kinase, and therefore can be expected to be disrupted by glyphosate in both of its enzymatic rôles. Mutations in PNKP have been shown to cause microcephaly, seizures and defects in DNA repair [300, 301].

Disrupted FOCM is an established risk factor for impaired neural tube closure leading to spina bifida and anencephaly [302, 241, 242]. Low maternal folate during the first trimester has been linked to increased risk to spina bifida, and this has inspired several governments to implement a folic acid enrichment programme for staple foods such as wheat-based products, although it is unclear whether the benefits of such programmes outweigh the risks [303]. Folate is synthesized from chorismate in both plants and gut microbes; chorismate is a product of the shikimate pathway that glyphosate disrupts [304].

FOCM operates in both the cytosol and the mitochondria. In the mitochondria, the reaction produces formate, a precursor to both purine synthesis and methyltetrahydrofolate, which plays an essential rôle in methylation pathways [302]. Impaired methylation capacity in the brain has been linked to autism [305, 306].

We mentioned the glycine cleavage system in the section on glycine riboswitches, where we suggested that impaired methylation capacity and glycine toxicity could arise due to glyphosate's disruption of this system in the gut microbes. An important regulatory enzyme in the GCS is glycine decarboxylase (GLDC). The lysine residue in human GLDC that binds to pyridoxal phosphate is very near a glycine-rich region that is essential for enzyme activity [307]. Embedded in a peptide sequence that is rich in β-turns and random coils, the glycine-rich region maintains shape and flexibility of the active site.

A study on mice with a deficiency in GLDC demonstrated two distinct outcomes: neural tube defects; and hydrocephalus with enlarged ventricles and non-ketotic hyperglycinaemia [243]. Autism, attention-deficit hyperactivity disorder (ADHD) and schizophrenia have all been linked to enlargement of the ventricles in the brain [308]. Children with prenatal mild ventriculomegaly had significantly larger cortical grey matter than controls and a large ratio of grey matter to white matter, both of which are features of autism [309]. Whole-genome sequencing applied to ASD families revealed links between autism and defective versions of the aminomethyl transferase gene (AMT) [310], another gene involved in glycine cleavage and linked to nonketotic hyperglycinaemia [311]. A case study concerned a boy with transient neonatal nonketotic hyperglycinaemia and autism [312]. Thus, it appears that autism, hyperglycinaemia and neural tube defects are all tied to impaired glycine cleavage and methylfolate deficiency, which can be explained by glyphosate's antibiotic effects as well as its interference with glycine riboswitches and with GLDC enzymatic action.

Another decarboxylase, besides GLDC, with a conserved active-site lysine near a glycine-rich sequence is ornithine decarboxylase (ODC) [313]. This enzyme is essential for the synthesis of spermidine and spermine, which stabilize DNA structure and assist in DNA repair mechanisms. Lack of ODC leads to apoptosis in embryonic mice following DNA damage [314]. Seizures, which are associated with autism [315], lead to an increased synthesis of ODC [316]. Could this be a compensatory reaction to diminishing activity in the context of glyphosate substitution for glycine in the active site?

Vanishing white matter (VWM) disease is a rare leukoencephalopathy caused by mutations in genes encoding the five subunits of eukaryotic translation initiation factor eIF2B [317]. In advanced cases, the white matter in the brain almost completely disappears, presenting a signal indicative of cerebrospinal fluid. Symptoms can include microcephaly, impaired swallowing, failure to thrive, epilepsy, growth retardation, dysgenesis of the ovaries, pancreatic abnormalities, hypoplastic kidneys, hepatosplenomegaly and cataracts, in addition to the leukoencephalopathy [318]. Increased levels of cerebrospinal glycine are a marker for the disease [318, 319], which may indicate neuroexcitotoxicity. A study of the genetic markers for several individual cases revealed mutations localized to two distinct regions containing highly conserved glycines [318]. One contained a single conserved glycine and the other exhibited the pattern GXXGXG.

The glycine receptor class (GlyRs) is a member of a family of ligand-gated ion channels. Glycine receptor activation is required for receptor clustering in spinal neurons, and is important in synaptogenesis [320]. This receptor is widely distributed in the nervous system, particularly in the spinal cord and brainstem [321]. Glycinergic inhibition plays an important rôle in motor

control, pain sensitization and respiratory rhythm [322]. It has been proposed that glyphosate may interfere with GlyR through glycine mimicry, and that this may increase risk to autism [13].

However, glyphosate may also operate at the level of residue substitution for glycine in the peptide sequence. An *in vitro* study on the human isoform by Vandenberget al. has confirmed that there is a conserved glycine residue, gly160, that forms part of the binding site and helps maintain the tertiary structure for binding [323]. Several mutations in GlyR α1 G160 significantly decrease the potency of glycine as an inhibitor, likely through disruption of glycine binding within the ligand-binding pocket [322].

9. IMPAIRED DEVELOPMENT AND INFERTILITY

A recent study by Coullery et al. has shown that glypyhosate causes irreversible abnormal growth and delayed development in neuronal cells taken from embryonic rats [324]. Cells exposed to sublethal levels of glyphosate exhibited shorter and unbranched axons and less complex dendritic arbours compared to controls. A deeper look into the underlying mechanism of toxicity revealed a decrease in WNT5a signaling, as well as downregulated Ca^{+2}/calmodulin-dependent protein kinase II (CaMKII) activity.

A possible mechanism by which CaMKII might be inhibited by glyphosate is through substitution of glyphosate for one of the highly conserved glycines near ser26. Ser26 is situated within a conserved stretch of nine residues (LGKGAFSVV) that constitute the upper lid of the ATP-binding site in the canonical kinase fold [325]. An intricate control mechanism for preventing excessive activity of this autophosphorylating enzyme involves phosphorylation of ser26, which then interferes with ATP binding and disrupts enzymatic activity in a feedback control mechanism. It was shown that replacement of serine with a negatively charged amino acid had the same effect as phosphorylation, inhibiting enzymatic activity. This suggests that the negative charge, repelling phosphate, is the deactivating agent. Replacement of one of the two nearby glycines with glyphosate would have a similar effect, thus explaining the enzyme inhibition that was observed in the Coullery et al. study.

Basigin, also known as extracellular matrix metalloproteinase inducer (EMMPRIN) and as cluster of differentiation 147 (CD147), is a member of the immunoglobulin superfamily, with a structure resembling the putative primordial form of this family. It plays many rôles in the body, particularly in development. Basigin contains a highly conserved glycine residue, gly181, within its extracellular domain, which is crucial for basigin-mediated signaling and chemotaxis [326]. It also has an important protective rôle in Alzheimer's disease, as it suppresses the production of Aβ [327]. Mutant mice lacking this gene showed impaired short-term memory and latent learning, as well as greater sensitivity to electric foot-shock [328]. Basigin is also critical in fetal development. Embryonic mice lacking basigin develop normally prior to implantation, but most of the embryos die around the time of implantation [329]. The male mice that survived into adulthood produced only a small number of spermatids that made it past the metaphase of the first meiosis. The female mice appeared normal but were probably defective in the step of implantation of the fertilized egg.

10. OTHER ENZYMES WITH CONSERVED GLYCINES

Adenosine 5-phosphosulfate kinase (APS kinase) is an important enzyme that participates in purine, selenoamino acid and sulfur metabolisms. In particular, it is the first and rate-limiting enzyme in methionine synthesis by gut microbes. Methionine is an essential amino acid in humans, and it sits at the crossroads of the methylation and transsulfuration pathways. Thus, we depend in part on our microbiome to synthesize methionine from APS. Glyphosate has been shown to deplete methionine levels in plants, which may be due to its ability to substitute for one or more conserved glycines in its polypeptide chain. APS kinase has been shown to be downregulated by a factor of –2.55 in *E. coli* upon exposure to glyphosate [330]. APS synthase contains an absolutely conserved N-terminal glycine [331].

The human equivalent of this enzyme, 3'-phospho-adenosine 5'-phosphosulfate (PAPS) synthase, is bifunctional—it has both a C-terminal ATP sulfurylase domain and an N-terminal APS kinase domain, connected by a short irregular linker [332]. The N-terminal glycine (gly59) is the initiator of a P-loop sequence, which plays an essential rôle in providing conformational flexibility. When the terminal glycine was experimentally substituted with alanine (a conservative substitution), sulfurylase activity dropped to only 8% of the original level [331]. PAPS formation was also disrupted when either the highly conserved gly59 or the highly conserved gly62 were substituted with alanine. The former alteration prevented the formation of the internal APS molecule, and the latter disrupted the final phosphorylation step. It can be expected that the P-loop's flexibility will also be severely restricted with the addition of a methylphosphonyl group to any of the conserved glycines, as would be the case with a substitution of glyphosate for glycine. PAPS plays an essential rôle in activating the usually highly inert sulfate anion to facilitate sulfoconjugation,

important for detoxifying xenobiotics as well as sulfurylation of sterols, polyphenols and neurotransmitters.

There are almost surely many enzymes with conserved glycines that we have not yet identified, which are also likely to be disrupted by glyphosate substitution for glycine. For example, the 65-amino acid γ subunit of Na,K-ATPase in kidney has a conserved glycine residue at position 4 which, if mutated to arginine or lysine, leads to an impaired ability to oligomerize [333]. This defect causes renal hypomagnesaemia, due to impaired magnesium reuptake in the renal tubules [334]. Acyl phosphatase, an active enzyme in muscles, enhances Na,K-ATPase activity [335], and a defective form could lead to impaired muscle function and heart failure [336]. Acylphosphatase has six conserved glycines [22]. One of them, gly15, is important for enzyme catalysis. The other five are suspected to play a rôle in preventing protein aggregation.

HapR is a quorum-sensing master regulator in *Vibrio cholerae*, controlling a wide range of physiological activities. In particular, it represses biofilm development and the production of primary virulence factors [337]. HapR has a conserved hinge glycine residue (gly39) that regulates its DNA binding ability, which is necessary for its regulatory control. Substitution of asparatate for gly39 renders the molecule nonfunctional.

Hydroxymethylglutaryl-coenzyme A (HMG-CoA) reductase is the enzyme that is suppressed by statin drugs to reduce serum cholesterol levels. The enzyme contains a glycine-rich region in the C-terminal section of the catalytic domain [338]. Necrotizing autoimmune myopathy (NAM) is a newly recognized condition characterized by idiopathic inflammatory myopathy, associated with necrosis in myocytes despite the absence of notable inflammation. This condition is associated with statin drug therapy, and a notable feature is that termination of statin therapy often does not alleviate symptoms [339]. Increased protein synthesis of HMG Co-A reductase can be expected following its suppressed activity level by statin drugs, and it is also upregulated in regenerating fibres following injury. Thus, it can be argued that overproduction of HMG Co-A reductase provides a greater opportunity for incorporating glyphosate into the enzyme, displacing conserved glycines. This would result in a malfunctioning of the enzyme and, possibly, also an autoimmune reaction to it due to impaired ability to metabolize damaged versions of the protein.

11. GLUFOSINATE: ANOTHER AMINO ACID ANALOGUE

Glufosinate, like glyphosate, is a broad-spectrum herbicide that may derive most of its toxicity from the fact that it is an amino acid analogue of glutamate [340]. In plants it inhibits glutamine synthetase, leading to a complete breakdown of ammonia metabolism.

Glufosinate adversely affects central nervous system development in both mice and rats. Glufosinate exposure to mouse embryos at different stages of development caused great disturbances to the nervous system [341]. Mouse embryos exposed to glufosinate at days 8 and 9 developed hypoplasia in the forebrain and visceral arches. Day 10 embryos exposed to glufosinate exhibited cleft lips as well as hypoplasia, along with significant cell death in the brain vesicle and neural tubes. Glufosinate inhibited the differentiation of midbrain cells in day 12 embryos.

Rats exposed to low doses of glufosinate in the first week of life were tested at six weeks and found to have an enhanced response to kainic acid, which stimulates glutamate receptors in the brain [342]. Glufosinate exposure of mouse dams has been shown to induce autistic-like behaviour in the pups [343]. Glutamate is a major excitatory neurotransmitter, and disrupted glutamate activity in the brain has been linked to autism [344].

Genetic defects for the encoding of the enzyme, asparagine synthetase, have been linked to microcephaly [345]. Asparagine synthetase has a conserved glutamate residue that is essential for its function [346]. There is a conserved glutamate residue in the first transmembrane domain in the entire family of major intrinsic protein (MIP) channels, which includes mammalian aquaporins. An equivalent neurogenic transmembrane protein in *Drosophila* is crucial for neuroblast determination during development [347].

Mutations in a conserved glutamate residue in the sulfonylurea receptor can result in either hyperinsulinism or neonatal diabetes [348]. Symptoms of neonatal diabetes include hyperglycaemia, failure to thrive, dehydration and ketoacidosis, which may lead to coma [349]. An absolutely conserved glutamate (E418) in all voltage-gated potassium channels has been shown to be critical to control the rate of slow inactivation [350].

Glutamate plays an essential rôle in ATPhydrolysis; DNA replication, which depends on ATP,is likely to be impaired if glufosinate can substitute for glutamate in peptides. The Walker B motif is a distinct sequence pattern found in ATP-binding proteins. It includes a conserved glutamate that is essential for ATPhydrolysis [351]. Replication factor C is a clamp loader that assists in the process of second-strand DNA synthesis. It has an absolutely conserved glutamate residue in a Walker B motif that is required for ATP-dependent ligand binding activity [352].

12. SUMMARIZING DISCUSSION

In this paper, we have reviewed the biological function of a large number of proteins containing conserved glycine residues and/or glycine-rich regions, in the light of the concept that glyphosate could be randomly substituting for glycine in these peptides, causing diverse negative consequences. There is strong evidence that glyphosate's mechanism of action includes an ability to substitute for glycine during protein synthesis. In fact, this can explain a large number of known effects of glyphosate on plants, microbes and eukaryotes, which are otherwise difficult to explain. For example, glyphosate's interference with oxidative phosphorylation [82] can now be easily understood through disruption of COX [89]. The disruption of PEPC that leads to impaired nitrogen fixation in plants exposed to glyphosate [226] is also explained through glyphosate substitution of an invariant glycine residue at the C-terminal. Glyphosate has been shown to inhibit iron uptake, and this may be due to both reduced synthesis of siderophores and impaired function of transporters of iron-carrying siderophores [257]. This may also directly explain the renal tubular disease that has become an epidemic among agricultural workers exposed to glyphosate [262], and which was demonstrated in Monsanto's own chronic long-term studies.

It is remarkable that conserved glycines are found in several of the misfolded proteins that are considered causal in prion diseases, Alzheimer's and Parkinson's diseases, and ALS [183, 184, 194, 209, 221, 222]. Substitution of glyphosate for invariant or highly conserved glycine residues in prion proteins, Aβ, α-synuclein and TDP-43 can explain the formation of the soluble, poorly hydrolysable forms of these pathogenic agents that are considered to be the most toxic species.

Prior research strongly supports the position that glyphosate would cause excessive phosphorylation cascade activity combined with impaired dephosphorylation capacity. This can be expected to lead to many diseased states, including cancer, diabetes and pathogen infectivity, particularly HIV [248], but perhaps most significantly, lung diseases such as pulmonary oedema, asthma and COPD [143].

There are many ways in which glyphosate substitution for conserved glycines could affect metabolism. One is through disruption of insulin signaling, particularly in the glucagon-producing cells in the liver, contributing to the recent worldwide epidemic of type 2 diabetes [80]. Another is through the disruption of glycine metabolism, which will result in a build-up of glycine to toxic levels while at the same time depleting the supply of methyl groups for one-carbon metabolism. This can easily link to spina bifida and other neural tube defects [243]. A third is through interference with the function of COX, which would have huge negative consequences for oxidative phosphorylation in the mitochondria, linked to many chronic diseases [87–89]. A fourth is through the impaired ability to export fatty acids from adipocyte stores, a clear path to obesity [48–50]. Impaired arylsulfatase activity is highly disruptive, as many biologically active molecules are sulfated during transit, and desulfation is a necessary step for activation [180]. The ability to produce sulfate anions to populate the extracellular matrix is also impaired, due to the fact that eNOS, a CYP enzyme, has conserved glycines in two regions, and their substitution by glyphosate can be predicted to cause both impaired ability to bind to caveolin in caveolae and impaired dimer formation [23, 167–170]. These two factors provide a plausible explanation for the well known pathology of superoxide production by eNOS in a "decoupled" state, which cannot be directed as intended towards sulfate synthesis [151, 152].

It is remarkable how well the epidemic of beak deformation in chickadees [103, 104] can be explained through the impaired ability of KEAP1 to bind to the cytoskeleton, leading to constitutive Nrf2 activation and overexpression of keratin synthesis. Since sunflower seeds in bird feeders are routinely sprayed with glyphosate just prior to harvest, there is a straightforward explanation for glyphosate contamination in the birds' diet. Overexpression of keratin also explains the inclusion bodies observed in human livers in association with fatty liver disease.

Non-Hodgkin's lymphoma, AIDS and glaucoma are other conditions whose potential link to glyphosate can be explained via displaced glycine residues in the conserved regions of various proteins [292, 290, 278, 223]. Hypothyroidism, pituitary disorder and adrenal insufficiency are also all potential consequences of displaced glycine residues. Collagen, a key protein in bones and joints, as well as the vasculature, is rich in glycines that are essential for the formation of cross-linkages that maintain the strength and elastic properties of the molecule. It is highly significant that mutations in collagen associated with genetic disorders almost always involve glycine residues [281–284]. This also highlights the essential rôle that glycine molecules play in this protein.

13. CONCLUSION

In this paper, we have shown that glyphosate, as an amino acid analogue of glycine, may be erroneously misincorporated into polypeptide chains during protein synthesis. The research literature documents evidence of severe protein impairment through substitution of conserved glycines by other amino acids. It leads to the

disruption of function of many proteins with essential rôles in metabolism and regulatory processes. Glyphosate substitution for conserved glycines in essential proteins can explain the destruction of glands and organs revealed by Monsanto (the original patent holder)'s own studies.

Glyphosate is pervasive in the food supply, and chronic exposure will lead to slow accumulation of damaged proteins, systemically. Fibrillary plaques and tangles intransigent to proteolysis may be due to glyphosate substitution for conserved glycines, accounting for multiple neurological diseases. Impairment in dimerization, membrane attachment, cytoskeleton attachment and active site flexibility are some of the defects we anticipate. Some consequences are impaired fatty acid release leading to obesity, impaired insulin receptor response leading to diabetes, impaired one-carbon metabolism leading to neural tube defects and autism, impaired oxidative phosphorylation causing mitochondrial disorders, impaired Nrf2 regulation leading to hyperkeratosis and fatty liver disease, impaired cell cycle control during DNA synthesis, impaired collagen cross-linking, and disregulated phosphorylation cascades leading to cancer, lung disorders, and autoimmune diseases. These effects easily account for the multitude of diseases and conditions whose incidence is rising in the USA and elsewhere, in step with the rise in the use of glyphosate on core crops. We urge regulatory agencies worldwide to take action to remove these synthetic amino acids not only from the food supply but from our biosphere.

REFERENCES

1. Dunlop, R.A., Cox, P.A., Banack, S.A. & Rodgers. K.J. The non-protein amino acid BMAA is misincorporated into human proteins in place of L-serine causing protein misfolding and aggregation. *PLoS ONE* **8** (2013) e75376.
2. Bell, E.A. Nonprotein amino acids of plants: significance in medicine, nutrition, and agriculture. *J. Agric. Food Chem.* **51** (2003) 2854–2865.
3. Rodgers, K.J., Wang, H., Fu, S. & Dean, R.T. Biosynthetic incorporation of oxidized amino acids into proteins and their cellular proteolysis. *Free Radical Biol. Med.* **32** (2002) 766–775.
4. Rodgers, K.J. & Shiozawa, N. Misincorporation of amino acid analogues into proteins by biosynthesis. *Intl J. Biochem. Cell Biol.* **40** (2008) 1452–1466.
5. Crine, P. & Lemieux, E. Incorporation of canavanine into rat pars intermedia proteins inhibits the maturation of pro-opiomelanocortin, the common precursor to adrenocorticotropin and beta-lipotropin. *J. Biol. Chem.* **257** (1982) 832–838.
6. Dunlop, R.A., Brunk, U.T. & Rodgers, K.J. Oxidized proteins: Mechanisms of removal and consequences of accumulation. *IUBMB Life* **61** (2009) 522–527.
7. Rubenstein, E. Biologic effects of and clinical disorders caused by nonprotein amino acids. *Medicine* **79** (2000) 80–89.
8. Godballe, T., Nilsson, L.L., Petersen, P.D. & Jenssen, H. Antimicrobial β-peptides and α-peptoids. *Chem. Biol. Drug Design* **77** (2011) 107–116.
9. Powers, J.C., Asgian, J.L., Ekici, O.D. & James, K.E. Irreversible inhibitors of serine, cysteine, and threonine proteases. *Chem. Rev.* **102** (2002) 4639–4750.
10. Sandeman, M., Duncan, A.M. & Chandler, D. Novel protease inhibitors for control of sheep blowfly and other insects. *Proc. FLICS Conf.*, Launceston (June 2001).
11. Kitchen, L.M., Witt, W.W. & Rieck, C.E. Inhibition of δ-aminolevulinic acid synthesis by glyphosate. *Weed Sci.* **29** (1981) 571–577.
12. Cattani, D., de Liz Oliveira Cavalli, V.L., Heinz Rieg, C.E., Domingues, J.T., Dal-Cim, T., Tasca, C.I., Mena Barreto Silva, F.R. & Zamoner, A. Mechanisms underlying the neurotoxicity induced by glyphosate-based herbicide in immature rat hippocampus: involvement of glutamate excitotoxicity. *Toxicology* **320** (2014) 34–45.
13. Beecham, J.E. & Seneff, S. The possible link between autism and glyphosate acting as glycine mimetic—A review of evidence from the literature with analysis. *J. Molec. Genet. Med.* **9** (2015) 4.
14. Rubenstein, E. Misincorporation of the proline analog azetidine-2-carboxylic acida in the pathogenesis of multiple sclerosis: a hypothesis. *J. Neuropathol. Exp. Neurol.* **67** (2008) 1035–1040.
15. Rosenthal, G.A. The biochemical basis for the deleterious effects of L-canavanine. *Phytochemistry* **30** (1990) 1055–1058.
16. Krakauer, J., Long Kolbert, A., Thanedar, S. & Southard, J. Presence of L-canavanine in Hedysarum alpinum seeds and its potential role in the death of Chris McCandless. *Wilderness Environ. Med.* **26** (2015) 36–42.
17. Li, Q., Lambrechts, M.J., Zhang, Q., Liu, S., Ge, D., Yin, R., Xi, M. & You, Z. Glyphosate and AMPA inhibit cancer cell growth through inhibiting intracellular glycine synthesis. *Drug Design Development Therapy* **7** (2013) 635–643.
18. Newman, M.M., Lorenz, N., Hoilett, N., Lee, N.R., Dick, R.P., Liles, M.R., Ramsier, C. & Kloepper, J.W. Changes in rhizosphere bacterial gene expression following glyphosate treatment. *Sci. Total Environ.* **553** (2017) 32–41.
19. Wang, W., Wu, Z., Dai, Z., Yang, Y., Wang, J. & Wu, G. Glycine metabolism in animals and humans: implications for nutrition and health. *Amino Acids* **45** (2013) 463–477.
20. Kostenis, E., Martini, L., Ellis, J., Waldhoer, M., Heydorn, A., Rosenkilde, M.M., Norregaard, P.K., Jorgensen, R., Whistler, J.L. & Milligan, G. A highly conserved glycine within linker I and the extreme C terminus of G protein alpha subunits interact cooperatively in switching G protein-coupled receptor-to-effector specificity. *J. Pharmacol. Exp. Ther.* **313** (2005) 78–87.
21. Jiang, Y., Lee, A., Chen, J., Cadene, M., Chait, B.T. & MacKinnon, R. The open pore conformation of potassium channels. *Nature* **417** (2002) 523–526.
22. Parrini, C., Taddei, N., Ramazzotti, M., Degl'Innocenti, D., Ramponi, G., Dobson, C.M. & Chiti, F. Glycine residues appear to be evolutionarily conserved for their ability to inhibit aggregation. *Structure* **13** (2005) 1143–1151.
23. Kamps, M.P., Buss, J.E. & Sefton, B. Mutation of NH2-terminal glycine of P60SWC prevents both myristoylation

and morphological transformation. *Proc. Natl Acad. Sci. USA* **82** (1985) 4625–4628.

24. Yan, B.X. & Sun, Y.Q. Glycine residues provide flexibility for enzyme active sites. *J. Biol. Chem.* **272** (1997) 3190–3194.
25. Pollack, P. *Fine Chemicals: The Industry and the Business*, 2nd edn. Hoboken: Wiley (2011).
26. Samsel, A. & Seneff, S. Glyphosate's suppression of cytochrome P450 enzymes and amino acid biosynthesis by the gut microbiome: Pathways to modern diseases. *Entropy* **15** (2013) 1416–1463.
27. Samsel, A. & Seneff, S. Glyphosate, pathways to modern diseases II: Celiac sprue and gluten intolerance. *Interdiscip. Toxicol.* **6** (2013) 159–184.
28. Samsel, A.& Seneff, S. Glyphosate, pathways to modern diseases III: Manganese neurological diseases, and associated pathologies. *Surg. Neurol. Intl* **6** (2015) 45.
29. Samsel, A. & Seneff, S. Glyphosate, pathways to modern diseases IV: cancer and related pathologies. *J. Biol. Phys. Chem.* **15** (2015) 121–159.
30. Swanson, N.L., Leu, A., Abrahamson, J. & Wallet, B. Genetically engineered crops, glyphosate and the deterioration of health in the United States of America. *J. Org. Systems* **9** (2014) 6–37.
31. Hoy. J., Swanson, N. & Seneff, S. The high cost of pesticides: human and animal diseases. *Poultry Fisheries Wildlife Sci.* **3** (2015) 1.
32. Howe, R.K., Chott, R.C. & McClanahan, R.H. *The Metabolism of Glyphosate in Sprague Dawley Rats. Part II. Identification, Characterization and Quantification of Glyphosate and its Metabolites after Intravenous and Oral Administration* (unpublished study MSL-7206 conducted by Monsanto and submitted to the EPA July 1988). MRID#407671-02 (1988).
33. Green, M.A. *The Metabolism of [C-14] Glyphosate in Optimum GAT (Event DP-098140-6) Field Corn* (Charles River Laboratories Project no. 807194, submitted by E.I. duPont de Nemours and Company). DuPont Report No. Dupont-19529 (2007).
34. Lowrie, C. *Metabolism of [14C]-N-Acetyl-Glyphosate (IN-MCX20) in the Lactating Goat* (Charles River Laboratories Project no. 210583, submitted by E. I. du Pont de Nemours and Company). DuPont Report No. DuPont-19796 (2007).
35. Lowrie, C. *The Metabolism of [C-14] N-Acetyl-Glyphosate (IN-MCX20) in Laying Hens* (Charles River Laboratories Project no.210573, submitted by E.I. duPont de Nemours and Company). DuPont Report No. Dupont-19795 (2007).
36. Md Abdur Rauf, S., Arvidsson, P.I., Albericio, F., Govender, T., Maguire, G.E., Kruger, H.G.& Honarparvar, B. The effect of N-methylation of amino acids (Ac-XOMe) on solubility and conformation: a DFT study. *Org. Biomolec. Chem.* **13** (2015) 9993–10006.
37. In vivo *Bone Marrow Cytogenetics Study of Glyphosate in Sprague Dawley Rats*. Li, A.P.& Folk, R.M. Monsanto Company Environmental Health Laboratory St Louis, Mo: (unpublished study dated 20 October 1983).
38. Harvey, A.N., Costa, N.D., Savage, J.R. & Thacker, J. Chromosomal aberrations induced by defined DNA double-strand breaks: The origin of achromatic lesions. *Somatic. Cell Molec. Genet.* **23** (1997) 211–219.
39. Sampath, H., Vartanian, V., Rollins, M.R., Sakumi, K., Nakabeppu, Y. & Lloyd, R.S. 8-Oxoguanine DNA glycosylase (OGG1) deficiency increases susceptibility to obesity and metabolic dysfunction. *PLoS ONE* **7** (2012) e51697.
40. Klungland, A., Rosewell, I., Hollenbach, S., Larsen, E., Daly, G., Epe, B., Seeberg, E., Lindahl, T. & Barnes, D.E. Accumulation of premutagenic DNA lesions in mice defective in removal of oxidative base damage. *Proc. Natl Acad. Sci. USA* **96** (1999) 13300–13305.
41. Hill, J.W., Hazra, T.K., Izumi, T. & Mitraa S. Stimulation of human 8-oxoguanine-DNA glycosylase by AP-endonuclease: potential coordination of the initial steps in base excision repair. *Nucl. Acids Res.* **29** (2001) 430–438.
42. Faucher, F., Doublié, S. & Jia, Z. 8-oxoguanine DNA glycosylases: one lesion, three subfamilies. *Intl J. Molec. Sci.* **13** (2012) 6711–6729.
43. Thameem, F., Puppala, S., Lehman, D.M., Stern, M.P., Blangero, J., Abboud, H.E., Duggirala, R. & Habib, S.L. The Ser(326)Cys polymorphism of 8-oxoguanine glycosylase 1 (OGG1) is associated with type 2 diabetes in Mexican americans. *Hum. Hered.* **70** (2010) 97–101.
44. Daimon, M., Oizumi, T., Toriyama, S., Karasawa, S., Jimbu, Y., Wada, K., Kameda, W., Susa, S., Muramatsu, M., Kubota, I., Kawata, S. & Kato, T. Association of the Ser326Cys polymorphism in the OGG1 gene with type 2 DM. *Biochem. Biophys. Res. Commun.* **386** (2009) 2629.
45. Beecham, J.E. & Seneff, S. Is there a link between autism and glyphosate-formulated herbicides? *J. Autism* **3** (2016) 1.
46. Pandey, A. & Rudraiah, M. Analysis of endocrine disruption effect of Roundup® in adrenal gland of male rats. *Toxicol. Rep.* **2** (2015) 1075–1085.
47. Holm, C., Davis, R.C., Osterlund, T., Schotz, M.C. & Fredrikson, G. Identification of the active site serine residue of hormone-sensitive lipase by site-specific mutagenesis. *FEBS Lett.* **344** (1994) 234–238.
48. Wilmouth, R.C., Edman, K., Neutze, R., Wright, P.A., Clifton, I.J., Schneider, T.R., Schofield, C.J. & Hajdu, J. X-ray snapshots of serine protease catalysis reveal a tetrahedral intermediate. *Nature Struct. Biol.* **8** (2001) 689–694.
49. Topf, M., Varnai, P., Schofield, C.J. & Richards, W.G. Molecular dynamics simulations of the acyl-enzyme and the tetrahedral intermediate in the deacylation step of serine proteases. *Proteins* **47** (2002) 357–369.
50. Topf, M., Varnai, P. & Richards, W.G.Ab initio QM/MM dynamics simulation of the tetrahedral intermediate of serine proteases: Insights into the active site hydrogenbonding network. *J. Am. Chem. Soc.* **124** (2002) 14780–14788.
51. Yeaman, S.J. Hormone-sensitive lipase—new roles for an old enzyme. *Biochem. J.* **379** (2004) 11–22.
52. Kraemer, F.B. & Shen, W.J. Hormone-sensitive lipase: Control of intracellular tri-(di-)acylglycerol and cholesteryl ester hydrolysis. *J. Lipid Res.* **43** (2002) 1585–1594.
53. Virk, A.P., Sharma, P. & Capalash, N. A new esterase, belonging to hormone-sensitive lipase family, cloned from Rheinheimera sp. isolated from industrial effluent. *J. Microbiol. Biotechnol.* **21** (2011) 667–674.
54. Kanaya, S., Koyanagi, T. & Kanaya, E. An esterase from Escherichia coli with a sequence similarity to hormone-

sensitive lipase. *Biochem. J.* **332** (1998) 75–80.

55. Mandrich, L., Menchise, V., Alterio, V., De Simone, G., Pedone, C., Rossi, M. & Manco, G. Functional and structural features of the oxyanion hole in a thermophilic esterase from *Alicyclobacillus acidocaldarius*. *Proteins* **71** (2008) 1721–1731.
56. Kratky, D., Obrowsky, S., Kolb, D. & Radovic, B. Pleiotropic regulation of mitochondrial function by adipose triglyceride lipase-mediated lipolysis. *Biochimie* **96** (2014) 106–112.
57. Simón, L. & Goodman, J.M. Enzyme catalysis by hydrogen bonds: The balance between transition state binding and substrate binding in oxyanion holes. *J. Org.Chem.* **75** (2010) 1831–1840.
58. Fuentes-Prior, P. & Salvesen, G.S. The protein structures that shape caspase activity, specificity, activation and inhibition. *Biochem. J.* **384** (2004) 201–232.
59. Lankas, G.R. & Hogan, G.K. *A Lifetime Feeding Study of Glyphosate (Roundup Technical) in Rats* (Project #77-2062). Unpublished study received 20 January 1982 under 524–308; Bio/dynamics Inc.; submitted by Monsanto to the EPA; Includes the study's 4-volume quality control evaluation of the Bio/dynamics assessment performed by Experimental Pathology Laboratories, Inc. (2,914 pp.). CDL:246617-A; 246618; 246619; 246620; 246621; MRID 00093879.
60. Kraemer, F.B. Adrenal cholesterol utilization. *Molec. Cell Endocrinol.* **265–266** (2007) 42–45.
61. Lia, N.G., Shib, Z.H., Tang, Y.P.& Duan, J.A. Selective matrix metalloproteinase inhibitors for cancer. *Current Med. Chem.***16** (2009) 3805–3827.
62. Jackson, D.S., Fraser, S.A., Ni, L.M., Kam, C.M., Winkler, U., Johnson, D.A., Froelich, C.J., Hudig, D. & Powers, J.C. Synthesis and evaluation of diphenyl phosphonate esters as inhibitors of the trypsin-like granzymes A and K and mast cell tryptase. *J. Med. Chem.* **41** (1998) 2289–301.
63. Modesto, K.A. & Martinez, C.B.R. Roundup causes oxidative stress in liver and inhibits acetylcholinesterase in muscle and brain of the fish Prochilodus lineatus. *Chemosphere* **78** (2010) 294–299.
64. Manning, G., Whyte, D.B., Martinez, R., Hunter, T. & Sudarsanam, S. The protein kinase complement of the human genome. *Science* **298** (2002) 1912–1934.
65. Knighton, D.R., Cadena, D.L., Zheng, J., Ten Eyck, L.F., Taylor, S.S., Sowadski, J.M. & Gill, G.N. Structural features that specify tyrosine kinase activity deduced from homology modeling of the epidermal growth factor receptor. *Proc. Natl Acad. Sci. USA* **90** (1993) 5001–5005.
66. Chaillot, D., Declerck, N., Niefind, K., Schomburg, D., Chardot, T. & Meunier, J.C. Mutation of recombinant catalytic subunit of the protein kinase CK2 that affects catalytic efficiency and specificity. *Protein Engng* **13** (2000) 291–298.
67. Hanks, S.K., Quinn, A.M. & Hunter, T. The protein kinase family: conserved features and deduced phylogeny of the catalytic domains. *Science* **241** (1988) 42–52.
68. Sternberg, M.J.E. & Taylor, W.R. Modelling the ATP-binding site of oncogene products, the epidermal growth factor receptor and related proteins. *FEBS Lett.* **175** (1984) 387–392.
69. Chow, J.P., Siu, W.Y., Ho, H.T., Ma, K.H., Ho, C.C. & Poon, R.Y.C. Differential contribution of inhibitory phosphorylation of CDC2 and CDK2 for unperturbed cell cycle control and DNA integrity checkpoints. *J. Biol. Chem.* **278** (2003) 40815–40828.
70. Bártoá, I., Otyepka, M., Kříž, Z. & Koča, J. Activation and inhibition of cyclindependent kinase-2 by phosphorylation; a molecular dynamics study reveals the functional importance of the glycine-rich loop. *Protein Sci.* **13** (2004) 1449–1457.
71. Litchfield, D.W. Protein kinase CK2: structure, regulation and role in cellular decisions of life and death. *Biochem. J* **369** (2003) 1–15.
72. Capdeville, R., Buchdunger, E., Zimmermann, J. & Matter, A. Glivec (STI571, imatinib), a rationally developed, targeted anticancer drug. *Nature Rev. Drug Discovery* **1** (2002) 493–502.
73. Cohen, P. Protein kinases—the major drug targets of the twenty-first century? *Nature Rev. Drug. Discovery* **1** (2002) 309–315.
74. Stamos, J.L., Chu, M. L.-H., Enos, M.D., Shah, M. & Weis, W.I. Structural basis of GSK-3 inhibition by N-terminal phosphorylation and by the Wnt receptor LRP6. *eLife* **3** (2014) e01998.
75. Hooper, C., Killick, R. & Lovestone, S. The GSK3 hypothesis of Alzheimer's disease. *J. Neurochem.* **104** (2008) 1433–1439.
76. Hoshi, M., Takashima, A., Noguchi, K., Murayama, M., Sato, M., Kondo, S., Saitoh, Y., Ishiguro, K., Hoshino, T. & Imahori, K. Regulation of mitochondrial pyruvate dehydrogenase activity by tau protein kinase I/glycogen synthase kinase 3β in brain. *Proc. Natl Acad. Sci. USA* **93** (1996) 2719–2723.
77. Cryer, P.E. Minireview: Glucagon in the pathogenesis of hypoglycemia and hyperglycemia in diabetes. *Endocrinology* **2153** (2012) 1039–1048.
78. Kawamori, D., Kurpad, A.J., Hu, J., Liew, C.W., Shih, J.L., Ford, E.L., Herrera, P.L., Polonsky, K.S., McGuinness, O.P. & Kulkarni, R.N. Insulin signaling in apha-cells modulates glucagon secretion in vivo. *Cell Metabolism* **9** (2009) 350–361.
79. Bajaj, M., Waterfield, M.D., Schlessinger, J., Taylor, W.R. & Blundell, T. On the tertiary structure of the extracellular domains of the epidermal growth factor and insulin receptors. *Biochim. Biophys. Acta* **916** (1987) 220–226.
80. Wertheimer, E., Barbetti, F., Muggeo, M., Roth, J. & Taylor, S.I. Two mutations in a conserved structural motif in the insulin receptor inhibit normal folding and intracellular transport of the receptor. *J. Biol. Chem.* **269** (1994) 7587–7592.
81. Barbetti, F., Gejman, P.V., Taylor, S.I., Raben, N., Cama, A., Bonora, E., Pizzo, P., Moghetti, P., Muggeo, M. & Roth, J. Detection of mutations in insulin receptor gene by denaturing gradient gel electrophoresis. *Diabetes* **41** (1992) 408–415.
82. Peixoto, F. Comparative effects of the Roundup and glyphosate on mitochondrial oxidative phosphorylation. *Chemosphere* **61** (2005) 1115–1122.
83. Kim, Y.-H., Hong, J.-R., Gil, H.-W., Song, H.-Y. & Hong, S.-Y. Mixtures of glyphosate and surfactant TN20 accelerate cell death via mitochondrial damage-induced apoptosis and necrosis. *Toxicol. in Vitro* **27** (2013) 191–197.
84. Wax, L.M., Leibl, R.M. & Bush, D.R. Surfactant-increased

glyphosphate uptake into plant membrane vesicles isolated from common lambsquateres leaves. *Plant Physiol.* **105** (1994) 1419–1425.

85. Mesnage, R., Defarge, N., de Vendômois, J.S. & Séralini, G.E. Potential toxic effects of glyphosate and its commercial formulations below regulatory limits. *Food Chem. Toxicol.* **84** (2015) 133–153.
86. Capaldi, R.A. Structure and function of cytochrome c oxidase. *A. Rev. Biochem.* **59** (1990) 569–596.
87. McDonald, W., Funatogawa, C., Li, Y., Chen, Y, Szundi, I., Fee, J.A., Stout, C.D. & Einarsdóttir, O. Conserved glycine 232 in the ligand channel of ba3 cytochrome oxidase from Thermus thermophilus. *Biochemistry* **53** (2014) 4467–4475.
88. Salomonsson, L., Lee, A., Gennis, R.B. & Brzezinski, P. A single-amino-acid lid renders a gas-tight compartment within a membrane-bound transporter. *Proc. Natl Acad. Sci. USA* **101** (2004) 11617–11621.
89. Wilson, T.M. & Cameron, V. Replacement of a conserved glycine residue in subunit II of cytochrome c oxidase interferes with protein function. *Curr. Genet.* **25** (1994) 233–238.
90. Holm, L., Saraste, M. & Wikstrom, M. Structural models of the redox centres in cytochrome oxidase. *EMBO J.* **6** (1987) 2819–2823.
91. Ma, Q. Role of Nrf2 in oxidative stress and toxicity. *A. Rev. Pharmacol. Toxicol.* **53** (2013) 401–426.
92. Ohta, T., Iijima, K., Miyamoto, M., Nakahara, I., Tanaka, H., Ohtsuji, M., et al. Loss of Keap1 function activates Nrf2 and provides advantages for lung cancer cell growth. *Cancer Res.* **68** (2008) 1303–1309.
93. Padmanabhan, B., Tong, K.I., Ohta, T., Nakamura, Y., Scharlock, M., Ohtsuji, M., Kang, M.I., Kobayashi, A., Yokoyama, S. & Yamamoto, M. Structural basis for defects of Keap1 activity provoked by its point mutations in lung cancer. *Molec. Cell* **21** (2006) 689–700.
94. Shibata, T., Kokubu, A., Gotoh, M., Ojima, H., Ohta, T., Yamamoto, M. & Hirohashi, S. Genetic alteration of Keap1 confers constitutive Nrf2 activation and resistance to chemotherapy in gallbladder cancer. *Gastroenterology* **135** (2008) 1358-1368 (and supplementary data).
95. Singh, A., Misra, V., Thimmulappa, R.K., Lee, H., Ames, S., Hoque, M.O., Herman, J.G., Baylin, S.B., Sidransky, D., Gabrielson, E., Brock, M.V. & Biswal, S. Dysfunctional Keap1-Nrf2 interaction in non-small-cell lung cancer. *PLoS Med.* **3** (2006) e420.
96. Rushworth, S.A. & MacEwan, D.J. The role of Nrf2 and cytoprotection in regulating chemotherapy resistance of human leukemia cells. *Cancers* **3** (2011) 1605–1621.
97. Shibata, T., Ohta, T., Tong, K.I., Kokubu, A., Odogawa, R., Tsuta, K., Asamura, H., Yamamoto, M. & Hirohashi, S. Cancer related mutations in Nrf2 impair its recognition by Keap1- Cul3 E3 ligase and promote malignancy. *Proc. Natl Acad. Sci. USA* **105** (2008) 13568–13573.
98. Suzuki, T., Maher, J. & Yamamoto, M. Select heterozygous Keap1 mutations have a dominant-negative effect on wild-type keap1 in vivo. *Cancer Res.* **71** (2010) 1700–1709.
99. Ogura, T., Tong, K.I., Mio, K., Maruyama, Y., Kurokawa, H., Sato, C. & Yamamoto, M. Keap1 is a forked-stem dimer structure with two large spheres enclosing the intervening, double glycine repeat, and C-terminal domains. *Proc. Natl Acad. Sci. USA* **107** (2010) 2842–2847.
100. Wakabayashi, N., Itoh, K., Wakabayashi, J., Motohashi, H., Noda, S., Takahashi, S., Imakado, S., Kotsuji, T., Otsuka, F., Roop, D.R., Harada, T., Engel, J.D. & Yamamoto, M. Keap1-null mutation leads to postnatal lethality due to constitutive Nrf2 activation. *Nature Genet.* **35** (2003) 238–245.
101. Kang, M.-I., Kobayashi, A., Wakabayashi, N., Kim, S.-G. & Yamamoto, M. Scaffolding of Keap1 to the actin cytoskeleton controls the function of Nrf2 as key regulator of cytoprotective phase 2 genes. *Proc. Natl Acad. Sci. USA* **101** (2004) 2046–2051.
102. Dinkova-Kostova, A.T., Holtzclaw, W.D., Cole, R.N., Itoh, K., Wakabayashi, N., Katoh, Y., Yamamoto, M. & Talalay, P. Direct evidence that sulfhydryl groups of Keap1 are the sensors regulating induction of phase 2 enzymes that protect against carcinogens and oxidants. *Proc. Natl Acad. Sci. USA* **99** (2002) 11908– 11913.
103. Handel, C.M., Pajot, L.M., Matsuoka, S.M., van HeMert, C., Terenzi, J., Talbot, S.L., Mulcahy, D.M., Meteyer C.U., & Trust, K.A. Epizootic of beak deformities among wild birds in Alaska: An emerging disease in North America? *Auk* **127** (2010) 882–898.
104. Handel, C.M. & van Hemert, C. Environmental contaminants and chromosomal damage associated with beak deformities in a resident North American passerine. *Environ. Toxicol. Chem.* **34** (2015) 314–327.
105. Gilbertson, M., Kubiak, T., Ludwig, J. & Fox, G. Great Lakes embryo mortality, edema, and deformities syndrome (GLEMEDS) in colonial fish-eating birds: Similarity to chick-edema disease. *J. Toxicol. Environ. Health* **33** (1991) 455520.
106. Gilbertson, M., Morris, R.D. & Hunter, R.A. Abnormal chicks and PCB residue levels in eggs of colonial birds on the lower Great Lakes (19711973). *Auk* **93** (1976) 434–442.
107. Ohlendorf, H.M. & Heinz, G.H. Selenium in birds. In: *Environmental Contaminants in Biota* (eds W.N. Beyer & J.P. Meador), 2nd edn, pp. 669–702. New York: CRC (2011).
108. Linz, G.M., Homan, H.J., Werner, S., Carlson, J.C. & Bleier, W.J. Sunflower growers use nonlethal methods to manage blackbird damage. In: *Proc. 14th WDM Conf.* (ed. S.N. Frey) (2012).
109. Sharp, M.S. & Neill, R.L. Physical deformities in a population of wintering blackbirds. *Condor* **81** (1979) 427430.
110. Schattenberg, J.M. & Schuppan, D. Nonalcoholic steatohepatitis: the therapeutic challenge of a global epidemic. *Curr. Opinion Lipidol.* **22** (2011) 479–488.
111. Singla, A., Moons, D.S., Snider, N.T., Wagenmaker, E.R., Jayasundera, V.B. & Omary, M.B. Oxidative stress, Nrf2 and keratin upregulation associate with Mallory-Denk body formation in mouse erythropoietic protoporphyria. *Hepatology* **56** (2012) 322–331.
112. Zatloukal, K., French, S.W., Stumptner, C., Strnad, P., Harada, M., Toivola, D.M., Cadrin, M. & Omary, M.B. From Mallory to Mallory–Denk bodies: What, how and why? *Exp. Cell Res.* **313** (2007) 2033–2049.
113. Bernstein, S.C., Lim, K.K., Brodland, D.G. & Heidelberg, K.A, The many faces of squamous cell carcinoma. *Dermatol. Surg.* **22** (1996) 243–254.
114. Yanofsky, V.R., Mercer, S.E. & Phelps, R.G.

Histopathological variants of cutaneous squamous cell carcinoma: A review. *J. Skin Cancer* **2011** (2011) 210813.

115. Crissman, J.D. Laryngeal keratosis and subsequent carcinoma. *Head Neck Surg.* **1** (1979) 386–391.

116. Taggart, M.W., Rashid, A., Ross, W.A. & Abraham, S.C. Oesophageal hyperkeratosis: clinicopathological associations. *Histopathology* **63** (2013) 463–473.

117. Stone, R.L. & Dixon, J.E. Protein-tyrosine phosphatases. *J. Biol. Chem.* **269** (1994) 31323–31326.

118. Zhuo, S., Clemens, I.C., Stone, R.L. & Dixon, J.E. Mutational analysis of a Ser/Thr phosphatase. Identification of residues important in phosphoesterase substrate binding and catalysis. *J. Biol. Chem.* **269** (1994) 26234–26238.

119. Bazan, J.F., Fletterick, R.J. & Pilkis, S.J. Evolution of a bifunctional enzyme: 6-phosphofructo-2-kinase/fructose-2,6-bisphosphatase. *Proc. Natl Acad. Sci. USA* **86** (1989) 9642–9646.

120. Stukey, J. & Carman, G.M. Identification of a novel phosphatase sequence motif. *Protein Sci.* **6** (1997) 469–472.

121. Zikherman, J. & Weiss, A. Unraveling the functional implications of GWAS: how T cell protein tyrosine phosphatase drives autoimmune disease. *J. Clin. Invest.* **121** (2011) 4618–4621.

122. Lorenz, U. SHP-1 and SHP-2 in T cells: two phosphatases functioning at many levels. *Immunol. Rev.* **228** (2009) 342–359.

123. Doody, K.M., Bussières-Marmen, S., Li, A., Paquet, M., Henderson, J.E., Tremblay, M.L. T cell protein tyrosine phosphatase deficiency results in spontaneous synovitis and subchondral bone resorption in mice. *Arthritis Rheumatism* **64** (2012) 752–761.

124. Wellcome Trust Case Control Consortium. Genome-wide association study of 14,000 cases of seven common diseases and 3,000 shared controls. *Nature* **447** (2007) 661–678.

125. Bottini, N., Musumeci, L., Alonso, A., Rahmouni, S., Nika, K., Rostamkhani, M., MacMurray, J., Meloni, G.F., Lucarelli, P., Pellecchia, M., Eisenbarth, G.S., Comings, D. & Mustelin, T. A functional variant of lymphoid tyrosine phosphatase is associated with type I diabetes. *Nature Genet.* **36** (2004) 337–338.

126. Kyogoku, C., Langefeld, C.D., Ortmann, W.A., Lee, A., Selby, S., Carlton, V.E., Chang, M., Ramos, P., Baechler, E.C., Batliwalla, F.M., Novitzke, J., Williams, A.H., Gillett, C., Rodine, P., Graham, R.R., Ardlie, K.G., Gaffney, P.M., Moser, K.L., Petri, M., Begovich, A.B., Gregersen, P.K. & Behrens, T.W. Genetic association of the R620W polymorphism of protein tyrosine phosphatase PTPN22 with human SLE. *Am. J. Hum. Genet.* **75** (2004) 504–507.

127. Begovich, A.B., Carlton, V.E., Honigberg, L.A., Schrodi, S.J., Chokkalingam, A.P., Alexander, H.C., Ardlie, K.G., Huang, Q., Smith, A.M., Spoerke, J.M., Conn, M.T., Chang, M., Chang, S.Y., Saiki, R.K., Catanese, J.J., Leong, D.U., Garcia, V.E., McAllister, L.B., Jeffery, D.A., Lee, A.T., Batliwalla, F., Remmers, E., Criswell, L.A., Seldin, M.F., Kastner, D.L., Amos, C.I., Sninsky, J.J. & Gregersen, P.K. A missense singlenucleotide polymorphism in a gene encoding a protein tyrosine phosphatase (PTPN22) is associated with rheumatoid arthritis. *Am. J. Hum. Genet.* **75** (2004) 330–337.

128. Doody, K.M., Bourdeau, A. & Tremblay, M.L. T-cell protein tyrosine phosphatase is a key regulator in immune cell signaling: lessons from the knockout mouse model and implications in human disease. *Immunol. Rev.* **228** (2009) 325–341.

129. Todd, J.A., Walker, N.M., Cooper, J.D., Smyth, D.J., Downes, K., Plagnol, V., Bailey, R., Nejentsev, S., Field, S.F., Payne, F., Lowe, C.E., Szeszko, J.S., Hafler, J.P., Zeitels, L., Yang, J.H., Vella, A., Nutland, S., Stevens, H.E., Schuilenburg, H., Coleman, G., Maisuria, M., Meadows, W., Smink, L.J., Healy, B., Burren, O.S., Lam, A.A., Ovington, N.R., Allen, J., Adlem, E., Leung, H.T., Wallace, C., Howson, J.M., Guja, C., Ionescu-Tîrgoviste, C., Simmonds, M.J., Heward, J.M., Gough, S.C.; Wellcome Trust Case Control Consortium, Dunger, D.B., Wicker, L.S. & Clayton, D.G. Robust associations of four new chromosome regions from genome-wide analyses of type 1 diabetes. *Nature Genet.* **39** (2007) 857–864.

130. Zeng, W.Y., Wang, Y.H., Zhang, Y.C., Yang, W.L. & Shi, Y.Y. Functional significance of conserved Glycine 127 in a human dual-specificity protein tyrosine phosphatase. *Biochemistry* (Moscow) **68** (2003) 634–638.

131. You-Ten, K.E., Muise, E.S., Itie, A., Michaliszyn, E., Wagner, J., Jothy, S., Lapp, W.S. & Tremblay, M.L. Impaired bone marrow microenvironment and immune function in T cell protein tyrosine phosphatase-deficient mice. *J. Exp. Med.* **186** (1997) 683–693.

132. Bourdeau, A., Dube, N., Heinonen, K.M., Theberge, J.F., Doody, K.M. & Tremblay, M.L. TC-PTP-deficient bone marrow stromal cells fail to support normal B lymphopoiesis due to abnormal secretion of interferon-. *Blood* **109** (2007) 4220–4228.

133. Heinonen, K.M., Nestel, F.P., Newell, E.W., Charette, G., Seemayer, T.A., Tremblay, M.L. & Lapp, W.S. T-cell protein tyrosine phosphatase deletion results in progressive systemic inflammatory disease. *Blood* **103** (2004) 3457–3464.

134. Wiede, F., Shields, B.J., Chew, S.H., Kyparissoudis, K., van Vliet, C., Galic, S., Tremblay, M.L., Russell, S.M., Godfrey, D.I. & Tiganis, T. T cell protein tyrosine phosphatase attenuates T cell signaling to maintain tolerance in mice. *J. Clin. Investigation* **121** (2011) 4758–774.

135. Kishihara, K., Penninger, J., Wallace, V.A., Kündig, T.M., Kawai, K., Wakeham, A., Timms, E., Pfeffer, K., Ohashi, P.S., Thomas, M.L., Furlonger, C., Paige, C.J. & Mak T.W. Normal B lymphocyte development but impaired T cell maturation in CD45-Exon6 protein tyrosine phosphatase-deficient mice. *Cell* **74** (1993) 143–156.

136. Hassan, S.W., Doody, K.M., Hardy, S., Uetani, N., Cournoyer, D. & Tremblay, M.L. Increased susceptibility to dextran sulfate sodium induced colitis in the T cell protein tyrosine phosphatase heterozygous mouse. *PLoS ONE* **5** (2010) e8868.

137. Beswick, E. & Millo, J. Fatal poisoning with GlySH surfactant herbicide. *J. Iran Chem. Soc.* **12** (2011) 379.

138. Thakur, D.S., Khot, R., Joshi, P.P., Pandharipande, M. & Nagpure, K. Glyphosate poisoning with acute pulmonary edema. *Toxicol. Intl* **21** (2014) 328–330.

139. Martinez, T.T., Long, W.C. & Hiller, R. Comparison of the toxicology of the herbicide Roundup by oral and pulmonary routes of exposure. *Proc. Western Pharmacol. Soc.* **33** (1990) 193–197.

140. Grinnell, K.L., Casserly, B. & Harrington, E.O. Role of protein tyrosine phosphatase SHP2 in barrier function of pulmonary endothelium. *Am. J. Physiol. Lung Cell Molec. Physiol.* **298** (2010) L361–L370.

141. Grinnell, K.L., Chichger, H., Braza, J., Duong, H. & Harrington, E.O. Protection against LPS-induced pulmonary edema through the attenuation of protein tyrosine phosphatase-1B oxidation. *Am. J. Respir Cell Molec. Biol.* **46** (2012) 623–632.

142. Kole, H.K., Smyth, M.S., Russt, P.L. & Burke, T.R., Jr. Phosphonate inhibitors of protein-tyrosine and serine/threonine phosphatases. *Biochem. J.* **311** (1995) 1025–1031.

143. Mercer, B.A. & D'Armiento, J.M. Emerging role of MAP kinase pathways as therapeutic targets in COPD. *Intl J. COPD* **1** (2006) 137–150.

144. Kishore, G.M. & Jacob, G.S. Degradation of glyphosate by Pseudomonas sp. PG2982 via a sarcosine intermediate. *J. Biol. Chem.* **262** (1987) 12164–12168.

145. Martínez-Solano, L., Macia, M., Fajardo, A., Oliver, A. & Martinez, J.L. Chronic *Pseudomonas aeruginosa* infection in chronic obstructive pulmonary disease. *Clin. Infectious Diseases* **47** (2008) 1526–1533.

146. Chang, F.C., Simcik, M.F. & Capel, P.D. Occurrence and fate of the herbicide glyphosate and its degradate aminomethylphosphonic acid in the atmosphere. *Environ. Toxicol. Chem.* **30** (2011) 548–555.

147. Krüger, M., Schrödl, W., Neuhaus, J. & Shehata, A.A. Field investigations of glyphosate in urine of Danish dairy cows. *J. Environ. Analyt. Toxicol.* **3** (2013) 1–7.

148. Hayashizaki, Y., Hiraoka, Y., Endo, Y., Miyai, K. & Matsubara, K. Thyroidstimulating hormone (TSH) deficiency caused by a single base substitution in the CAGYC region of the beta-subunit. *EMBO J.* **8** (1989) 2291–2296.

149. Collares, C.V., Antunes-Rodrigues, J., Moreira, A.C., Franca, S.N., Pereira, L.A., Soares, M.M., Elias J., Jr., Clark, A.J., de Castro, M. & Elias, L.L. Heterogeneity in the molecular basis of ACTH resistance syndrome. *Eur. J. Endocrinol.* **159** (2008) 61–68.

150. Cockcroft, J.R. Exploring vascular benefits of endothelium-derived nitric oxide. *Am. J. Hypertension* **18** (2005) 177S–183S.

151. Hijmering, E.M., van Zandvoort, M., Wever, R., Rabelink, T.J. & van Faassen, E.E. Origin of superoxide production by endothelial nitric oxide synthase. *FEBS Lett.* **438** (1998) 161–164.

152. Vá squez-Vivar, J., Kalyanaraman, B., Martásek, P., Hogg, N., Siler Masters, B.S., Karoui, H., Tordo, P. & Pritchard, K.A. Jr. Superoxide generation by endothelial nitric oxide synthase: The influence of cofactors. *Proc. Natl Acad. Sci. USA* **95** (1998) 9220– 9225.

153. Ostrom, R.S., Bundey, R.A. & Insel, P.A. Nitric oxide inhibition of adenylyl cyclase type 6 activity is dependent upon lipid rafts and caveolin signaling complexes. *J. Biol. Chem.* **279** (2004) 19846–19853.

154. Ju, H., Zou, R., Venema, V.J. & Venema, R.C. Direct interaction of endothelial nitricoxide synthase and caveolin-1 inhibits synthase activity. *J. Biol. Chem.* **272** (1997) 18522–18525.

155. Michel, T., Li, G. & Busconi, L. Phosphorylation and subcellular translocation of endothelial nitric oxide synthase. *Proc. Natl Acad. Sci. USA* **90** (1993) 6252–6256.

156. Takahashi, S. & Mendelsohn, M.E. Calmodulin-dependent and -independent Activation of Endothelial Nitric-oxide Synthase by Heat Shock Protein 90. *J. Biol. Chem.* **278** (2003) 9339–9344.

157. Seneff, S., Lauritzen, A., Davidson, R. & Lentz-Marino, L. Is endothelial nitric oxide synthase a moonlighting protein whose day job is cholesterol sulfate synthesis? Implications for cholesterol transport, diabetes and cardiovascular disease. *Entropy* **14** (2012) 2492–2530.

158. Seneff, S., Davidson, R.M., Lauritzen, A., Samsel, A. & Wainwright, G. A novel hypothesis for atherosclerosis as a cholesterol sulfate deficiency syndrome. *Theor. Biol. Med. Modeling* **12** (2015) 9.

159. Rohwerder, T. & Sand, W. The sulfane sulfur of persulfides is the actual substrate of the sulfur-oxidizing enzymes from Acidithiobacillus and Acidiphilium spp. *Microbiology* **149** (2003) 1699–1710.

160. Ida, T., Sawa, T., Ihara, H., Tsuchiya, Y., Watanabe, Y., Kumagai, Y., Suematsu, M., Motohashi, H., Fujii, S., Matsunaga, T., Yamamoto, M., Ono, K., Devarie-Baez, N.O., Xian, M., Fukuto, J.M. & Akaike, T. Reactive cysteine persulfides and S-polythiolation regulate oxidative stress and redox signaling. *Proc. Natl Acad. Sci. USA* **111** (2014) 7606–7611.

161. Kang, E.S., Ford, K., Grokulsky, G., Wang, Y.B., Chiang, T.M. & Acchiardo, S.R. Normal circulating adult human red blood cells contain inactive NOS proteins. *J. Lab. Clin. Med.* **135** (2000) 444–451.

162. Bleau, G., Bodley, F.H., Longpre, J., Chapdelaine, A. & Roberts, K.D. Cholesterol sulfate I. Occurrence and possible function as an amphipathic lipid in the membrane of the human erythrocyte. *Biochim. Biophys. Acta* **352** (1974) 1–9.

163. Bleau, G., Lalumiere, G., Chapdelaine, A. & Roberts, K.D. Red cell surface structure. Stabilization by cholesterol sulfate as evidenced by electron microscopy. *Biochim. Biophys. Acta* **375** (1975) 220–223.

164. Venema, R.C., Ju, H., Zou, R., Ryan, J.W. & Venema, V.J. Subunit interactions of endothelial nitric-oxide synthase: Comparisons to the neuronal and inducible nitric-oxide synthase isoforms. *J. Biol. Chem.* **272** (1997) 1276–1282.

165. Cho, H.J., Martin, E., Xie, Q., Sassa, S. & Nathan, C. Inducible nitric oxide synthase: identification of amino acid residues essential for dimerization and binding of tetrahydrobiopterin. *Proc. Natl Acad. Sci. USA* **92** (1995) 11514–11518.

166. Sessa, W.C., Barber, C.M. & Lynch, K.R. Mutation of N-myristoylation site converts endothelial cell nitric oxide synthase from a membrane to a cytosolic protein. *Circulation Res.* **72** (1993) 921–924.

167. Venema, R.C., Sayegh, H.S., Arnal, J.F. & Harrison, D.G. Role of the enzyme calmodulin-binding domain in membrane association and phospholipid inhibition of endothelial nitric oxide synthase. *J. Biol. Chem.* **270** (1995) 14705–4711.

168. Busconi, L. & Michel, T. Endothelial nitric oxide synthase. N-terminal myristoylation determines subcellular localization. *J. Biol. Chem.* **268** (1993) 8410–8413.

169. Liu, J., Garc□-a-Carde~na, G. & Sessa, W.C. Biosynthesis and palmitoylation of endothelial nitric oxide synthase:

mutagenesis of palmitoylation sites, cysteines-15 and/or -26, argues against depalmitoylation-induced translocation of the enzyme. *Biochem.* **34** (1995) 12333–41230.

170. Robinson, L.J. & Michel, T. Mutagenesis of palmitoylation sites in endothelial nitric oxide synthase identifies a novel motif for dual acylation and subcellular targeting. *Proc. Natl Acad. Sci. USA* **92** (1995) 11776–11780.

171. Aitken, A., Cohen, P., Santikarn, S., Williams, D.H., Calder, A.G., Smith, A. & Klee, C.B. Identification of the NH2-terminal blocking group of calcineurin B as myristic acid. *FEBS Lett.* **150** (1982) 314–318.

172. Carr, S.A., Biemann, K., Shoji, S., Parmelee, D.C. & Titani, K. n-Tetradecanoyl is the NH2-terminal blocking group of the catalytic subunit of cyclic AMP-dependent protein kinase from bovine cardiac muscle. *Proc. Natl Acad. Sci. USA* **79** (1982) 61286131.

173. Bé ven, L., Adenier, H., Kichenama, R., Homand, J., Redeker, V., Le Caer, J.P., Ladant, D. & Chopineau, J. Ca^{2+}-myristoyl switch and membrane binding of chemically acylated neurocalcins. *Biochemistry* **40** (2001) 8152–60.

174. Henderson, L.E., Krutzsch, H.C. & Oroszlan, S. Myristyl amino-terminal acylation of murine retrovirus proteins: an unusual post-translational proteins modification. *Proc. Natl Acad. Sci. USA* **80** (1983) 339–343.

175. Bur goyne, R.D. & Weiss, J.L. The neuronal calcium sensor family of Ca^{2+}-binding proteins. *Biochem. J.* **353** (2001) 1–12.

176. Ivings, L., Pennington, S.R., Jenkins, R., Weiss, J.L. & Burgoyne, R.D. Identification of Ca^{2+}-dependent binding partners for the neuronal calcium sensor protein neurocalcin : interaction with actin, clathrin and tubulin. *Biochem. J.* **363** (2002) 599–608.

177. Fang, F.C. Mechanisms of nitric oxide-related antimicrobial activity. *J. Clin. Invest.* **99** (1997) 2818–2825.

178. Bif fi, A., Lucchini, G., Rovelli, A. & Sessa, M. Metachromatic leukodystrophy: an overview of current and prospective treatments. *Bone Marrow Transplantation* **42** (2008) S2–S6.

179. Lukatela, G., Krauss, N., Theis, K., Selmer, T., Gieselmann, V., von Figura, K. & Saenger, W. Crystal structure of human arylsulfatase A: The aldehyde function and the metal ion at the active site suggest a novel mechanism for sulfate ester hydrolysis. *Biochemistry* **37** (1998) 3654–3664.

180. Dierks T, Schmidt B, and von Figura K. (1997) Conversion of cysteine to formylglycine: a protein modification in the endoplasmic reticulum. *Proc. Natl Acad. Sci. USA* **94** (1997) 11963–11968.

181. Dierks, T., Lecca, M.R., Schlotterhose, P., Schmidt, B. & von Figura, K. Sequence determinants directing conversion of cysteine to formylglycine in eukaryotic sulfatases. *EMBO J.* **18** (1999) 2084–2091.

182. Hsiao, E.Y., McBride, S.W., Hsien, S., Sharon, G., Hyde, E.R., McCue, T., Codelli, J.A., Chow, J., Reisman, S.E., Petrosino, J.F., Patterson, P.H. & Mazmanian, S.K. Microbiota modulate behavioral and physiological abnormalities associated with neurodevelopmental disorders. *Cell* **155** (2013) 1451–1463.

183. Harrison, C.F., Lawson, V.A., Coleman, B.M., Kim, Y.-S., Masters, C.L., Cappai, R., Barnham, K.J. & Hill, A.F. Conservation of a glycine-rich region in the prion protein is required for uptake of prion infectivity. *J. Biol. Chem.* **285** (2010) 20213–20223.

184. Florio, T., Paludi, D., Villa, V., Rossi Principe, D., Corsaro, A., Millo, E., Damonte, G., d'Arrigo, C., Russo, C., Schettini, G. & Aceto, A. Contribution of two conserved glycine residues to fibrillogenesis of the 106-126 prion protein fragment. Evidence that a soluble variant of the 106-126 peptide is neurotoxic. *J. Neurochem.* **85** (2003) 62–72.

185. T agliavini, F., Prelli, F., Verga, L., Giaccone, G., Sarma, R., Gorevic, P., Ghetti, B., Passerini, F., Ghibaudi, E., Forloni, G. et al. Synthetic peptides homologous to prion protein residues 106-147 form amyloid-like fibrils in vitro. *Proc. Natl Acad. Sci. USA* **90** (1993) 9678–9682.

186. R ymer, D. & Good, T.A. The role of prion peptide structure and aggregation in toxicity and membrane binding. *J. Neurochem.* **75** (2000) 2536–2545.

187. Buc ciantini, M., Giannoni, E., Chiti, F., Baroni, F., Formigli, L., Zurdo, J., Taddei, N., Ramponi, G., Dabsan, C.M. & Stefani, M. Inherent toxicity of aggregates implies a common mechanism for protein misfolding diseases. *Nature* **416** (2002) 507–511.

188. McGrath, J.W., Chin, J.P. & Quinn, J.P. Organophosphonates revealed: new insights into the microbial metabolism of ancient molecules. *Nature Rev. Microbiol.* **11** (2013) 412– 419.

189. Bleiler, T.W. Alzheimer's disease facts and figures. *Alzheimer's Dementia* **9** (2013) 208– 245.

190. Goure, W.F., Krafft, G.A., Jerecic, J. & Hefti, F. Targeting the proper amyloid-beta neuronal toxins: a path forward for Alzheimer's disease immunotherapeutics. *Alzheimer's Res. Ther.* **6** (2014) 42.

191. Selkoe, D.J. Alzheimer's disease results from the cerebral accumulation and cytotoxicity of amyloid β-protein. *J. Alzheimer's Dis.* **3** (2001) 75–80.

192. Holmes, C., Boche, D., Wilkinson, D., Yadegarfar, G., Hopkins, V., Bayer, A., Jones, R.W., Bullock, R., Love, S., Neal, J.W., Zotova, E. & Nicoll, J.A. Long-term effects of Abeta42 immunisation in Alzheimer's disease: Follow-up of a randomised, placebocontrolled phase I trial. *Lancet* **72** (2008) 216–223.

193. Nicoll, A.J., Panico, S., Freir, D.B., Wright, D., Terry, C., Risse, E., Herron, C.E., O'Malley, T., Wadsworth, J.D.F., Farrow, M.A., Walsh, D.M., Saibil, H.R. & Collinge, J. Amyloid-β nanotubes are associated with prion protein-dependent synaptotoxicity. *Nature Commun.* **4** (2013) 2416.

194. Munter, L.-M., Voigt, P., Harmeier, A., Kaden, D., Gottschalk, K.E., Weise, C., Pipkorn, R., Schaefer, M., Langosch. D. & Multhaup, G. GxxxG motifs within the amyloid precursor protein transmembrane sequence are critical for the etiology of Ab42. *EMBO J.* **26** (2007) 1702–1712.

195. Durlach, J. Magnesium depletion and pathogenesis of Alzheimer's disease. *Magnesium Res.* **3** (1990) 217–218.

196. Glick, J.L. Dementias: the role of magnesium deficiency and a hypothesis concerning the pathogenesis of Alzheimer's disease. *Med. Hypotheses* **31** (1990) 211–225.

197. Yu, J., Sun, M., Chen, Z., Lu, J., Liu, Y., Zhou, L., Xu, X., Fan, D. & Chui, D. Magnesium modulates amyloid-beta protein precursor trafficking and processing. *J. Alzheimer'sDis.* **20** (2010) 1091–106.

198. Duke, S.O., Vaughn, K.C. &Wauchope, R.D. Effects of

glyphosate on uptake, translocation, and intracellular localization of metal cations in soybean (Glycine max) seedlings. *Pesticide Biochem. Physiol.* **24**(3) (1985) 384–394.

199. Cakmak, I., Yazici, A., Tutus, Y.& Ozturk, L. Glyphosate reduced seed and leaf concentrations of calcium, manganese, magnesium, and iron in non-glyphosate resistant soybean. *Eur.J. Agronomy* **31** (2009) 114–119.

200. Bush, A.I., Pettingell, W.H., Multhaup, G., Paradis, M., Vonsattel,J.P.,Gusella, J.F., Beyreuther, K., Masters, C.L. & Tanzi, R.E. Rapid induction of Alzheimer A beta amyloid formation by zinc. *Science* **265** (1994) 1464–1467.

201. Lovell, M.A., Robertson, J.D., Teesdale, W.J.,Campbell, J.L. & Markesbery, W.R. Copper, iron and zinc in Alzheimer's disease senile plaques. *J. Neurol. Sci.* **158** (1998) 47–52.

202. Opazo, C., Huang, X., Cherny, R.A., Moir, R.D., Roher, A.E., White, A.R., Cappai, R., Masters, C.L., Tanzi, R.E., Inestrosa, N.C. & Bush, A.I. Metalloenzyme-like activity of Alzheimer's disease β-amyloid. Cu-dependent catalytic conversion of dopamine, cholesterol, and biological reducing agents to neurotoxic H_2O_2. *J. Biol. Chem.* **277** (2002) 40302–40308.

203. Maynard, C.J., Bush, A.I., Masters, C.L., Cappai, R. & Li, Q.-X.. Metals and amyloid-β in Alzheimer's disease. *Intl J. Exp. Path* **86** (2005) 147–159.

204. Religa, D., Strozyk, D., Cherny, R.A., Volitakis, I., Haroutunian, V., Winblad, B., Naslund, J. & Bush, A.I. Elevated cortical zinc in Alzheimer disease. *Neurology* **67** (2006) 69–75.

205. Kawahara, M. & Kato-Negishi, M. Link between aluminum and the pathogenesis of Alzheimer's disease: The integration of the aluminum and amyloid cascade hypotheses. *Intl J. Alzheimer's Dis.* **2011** (2011) 276393.

206.Buée, L., Bussière, T., Buée-Scherrer, V.,Delacourte, A. & Hof, P.R. Tau protein isoforms, phosphorylation and role in neurodegenerative disorders. *Brain Res. Rev.* **33** (2000) 95–130.

207. Murayama, H., Shin, R.-W., Higuchi, J., Shibuya, S., Muramoto, T. & Kitamoto, T. Interaction of aluminum with PHFtau in Alzheimer's disease neurofibrillary degeneration evidenced by desferrioxamine-assisted chelating autoclave method. *Am. J. Pathol.* **155** (1999) 877–885.

208.Pur gel, M., Takács, Z., Jonsson, C.M., Nagy, L., Andersson, I., Bányai, I., Pápai, I., Persson, P., Sjöberg, S. & Tóth, I. Glyphosate complexation to aluminium(III). An equilibrium and structural study in solution using potentiometry, multinuclear NMR, ATRFTIR, ESI-MS and DFT calculations. *J. Inor. Biochem.* **103** (2009) 1426–1438.

209. Dahlgren, K.N., Manelli, A.M., Stine, W.B.Jr., Baker, L.K., Krafft, G.A.& LaDu, M.J. Oligomeric and fibrillar species of amyloid-beta peptides differentially affect neuronal viability. *J. Biol. Chem.* **277** (2002) 32046–32053.

210.Walsh, D.M., Klyubin, I., Fadeeva, J.V., Cullen, W.K., Anwyl, R., Wolfe, M.S., Rowan, M.J. & Selkoe, D.J. Naturally secreted oligomers of amyloid beta protein potently inhibit hippocampal long-term potentiation *in vivo*. *Nature* **416** (2002) 535–539.

211. Hu, M.-W., Nicoll, A.J., Zhang, D., Mably, A.J., O'Malley, T., Purro, S.A., Terry, C., Collinge, J., Walsh, D.M. & Rowan, M.J. mGlu5 receptors and cellular prion protein mediate amyloid-β-facilitated synaptic long-term depression in vivo. *Nature Commun.* **5** (2014) 3374.

212. Freir, D.B., Nicoll, A.J., Klyubin, I., Panico, S., McDonald, J.M., Risse, E. & Asante, E.A. Interaction between prion protein and toxic amyloid beta assemblies can be therapeutically targeted at multiple sites. *Nature Commun.* **2** (2011) 336.

213. Meehan, S., Berry, Y.,Luisi, B., Dobson, C.M., Carver, J.A. & MacPheea, C.E. Amyloid fibril formation by lens crystallin proteins and its implications for cataract formation. *J. Biol. Chem.* **279** (2004) 3413–3419.

214. Goldstein, L.E., Muffat, J.A., Cherny, R.A., Moir, R.D., Ericsson, M.H., Huang, X., Mavros. C., Coccia, J.A., Faget, K.Y.,Fitch, K.A., Masters, C.L., Tanzi, R.E., Chylack, L.T. Jr. & Bush, A.I. Cytosolic beta-amyloid deposition and supranuclear cataracts in lenses from people with Alzheimer's disease. *Lancet* **361** (2003) 1258–1265.

215. Lin, H.J., Lai, C.C., Huang, S.Y.,Hsu, W.Y.& Tsai, F.J. An Increase in Phosphorylation and Truncation of Crystallin With the Progression of Cataracts. *Current Therapeutic Res.* **74** (2013) 9–15.

216. Singh, D., Raman, B., Ramakrishna, T. & Rao, C.M. The cataract-causing mutation G98R in human αA-crystallin leads to folding defects and loss of chaperone activity. *Molec. Vision* **12** (2006) 1372–1379.

217. Han, H., Weinreb, P.H. & Lansbury, P.T. Jr. The core Alzheimer's peptide NAC forms amyloid fibrils which seed and are seeded by beta-amyloid: is NAC a common trigger or target in neurodegenerative disease? *Chem. Biol.* **2** (1995) 163–169.

218. Spillantini, M.G.,Schmidt, M.L., Lee, V.M.,Trojanowski, J.Q., Jakes, R. & Goedert, M. Alpha-synuclein in Lewy bodies. *Nature* **388** (1997) 839–840.

219. Mezey, E., Dehejia, A., Harta, G., Papp, M.I., Polymeropoulos, M.H. & Brownstein, M.J. Alpha synuclein in neurodegenerative disorders: murderer or accomplice? *Nature Med.* **4** (1998) 755–757.

220. El-Agnaf, O.M.A., Salem, S.A., Paleologou, K.E., Curran, M.D., Gibson, M.J., Court, J.A., Schlossmacher, M.G. & Allsop, D. Detection of oligomeric forms of -synuclein protein in human plasma as a potential biomarker for Parkinson's disease. *FASEBJ.* **20** (2006) 419–425.

221. Du, H.-N., Tang. L., Luo. X.-Y.,Li, H.-T., Hu, J., Zhou, J.-W. & Hu, H.-Y. A peptide motif consisting of glycine, alanine, and valine is required for the fibrillization and cytotoxicity of human α-Synuclein. *Biochemistry* **42** (2003) 8870–8878.

222. Pesiridis, S., Lee, V.M.-Y.& Trojanowski, J.Q. Mutations in TDP-43 link glycinerich domain functions to amyotrophic lateral sclerosis. *Hum. Mol. Genet.* **18** (2009) R156–R162.

223. Ou, S.H., Wu, F., Harrich, D., Garca-Martínez, L.F. & Gaynor, R.B. Cloning and characterization of a novel cellular protein, TDP-43, that binds to human immunodeficiency virus type 1 TAR DNA sequence motifs. *J. Virol.* **69** (1995) 3584–3596.

224. Guo, W.,Chen, Y.,Zhou, X., Kar, A., Ray, P.,Chen, X., Rao, E.J., Yang, M., Ye, H., Zhu, L., Liu, J., Xu, M., Yang, Y., Wang, C., Zhang, D., Bigio, E.H., Mesulam, M., Shen, Y., Xu, Q., Fushimi, K. & Wu, J.Y. An ALS-associated mutation affecting TDP-43 enhances protein aggregation, fibril formation and neurotoxicity. *Nature Struct. Molec. Biol.* **18** (2011) 822–830.

225. Gurney, M.E., Pu, H., Chiu, A.Y., Dal Canto, M.C., Polchow, C.Y., Alexander, D.D., Caliendo, J., Hentati, A., Kwon, Y.W., Deng, H.X., et al. Motor neuron degeneration in mice that express a human Cu,Zn superoxide dismutase mutation. *Science* **264** (1994) 1772–1775.

226. Zaidi, A., Khan, M.S. & Rizvi, P.Q. Effect of herbicides on growth, nodulation and nitrogen content of greengram. *Agron. Sustainable Development* **25** (2005) 497–504.

227. Su, L.Y., DelaCruz, A., Moore, P.H. & Maretzki, A. The relationship of glyphosate treatment to sugar metabolism in sugarcane: new physiological insights. *J. Plant Physiol.* **140** (1992) 168–173.

228. de María, N., Becerril, J.M., Garca-Plazaola, J.I., Hernandez, A., de Felipe, M.R. & Fernandez-Pascual, M. New insights on glyphosate mode of action in nodular metabolism: Role of shikimate accumulation. *J. Agric. Food Chem.* **54** (2006) 2621–2628.

229. Gomes da Silveira, J.A., Contado, J.L., Mazza Rodrigues, J.L. & Abreu de Oliveira, J.T. Phosphoenolpyruvate carboxylase and glutamine synthetase activities in relation to nitrogen fixation in cowpea nodules. *Revista Brasileira de Fisiologia Vegetal* **10** (1998) 19–23.

230. Chollet, R., Vidal, J. & O'Leary, M.H. Phospho-enolpyruvate carboxylase: A ubiquitous, highly regulated enzyme in plants. *A. Rev. Plant Physiol. Plant Mol. Biol.* **47** (1996) 273–298.

231. Xu, W., Ahmed, S., Moriyama, H. & Chollet, R. The importance of the strictly conserved, C-terminal glycine residue in phosphoenolpyruvate carboxylase for overall catalysis: mutagenesis and truncation of GLY-961 in the sorghum C4 leaf isoform. *J. Biol. Chem.* **281** (2006) 17238–17245.

232. Damin, V., Junqueira Franco, H.C., Ferreira Moraes, M., Franco, A.K &, Ocheuze Trivelin, P.C. Nitrogen loss in Brachiaria decumbens after application of glyphosate or glufosinate-ammonium. *Sci. Agric.* (Piracicaba, Brazil) **65** (2008) 402–407.

233. Minami, M., Ando, T., Hashikawa, S.N., Torii, K., Hasegawa, T., Israel, D.A., Ina, K., Kusugami, K., Goto, H. & Ohta, M. Effect of glycine on Helicobacter pylori in Vitro. *Antimicrob. Agents Chemother.* **48** (2004) 3782–3788.

234. Snell, E.E. & Guirard, B.M. Some interrelationships of pyridoxine, alanine, and glycine in their effect on certain lactic acid bacteria. *Proc. Natl Acad. Sci. USA* **29** (1943) 66–73.

235. Gordon, J., Hall, R.A. & Stickland, L.H. A comparison of the degree of lysis by glycine of normal and glycine-resistant organisms. *J. Pathol. Bacteriol.* **61** (1949) 581–585.

236. Hishinuma, F., Izaki, K. & Takahashi, H. Effects of glycine and D-amino acids on growth of various microorganisms. *Agric. Biol. Chem.* **33** (1969) 1577–1586.

237. Tezuka, T. & Ohnishi, Y. Two glycine riboswitches activate the glycine cleavage system essential for glycine detoxification in Streptomyces griseus. *J. Bacteriol.* **196** (2014) 1369–1376.

238. Strominger, J.L. & Birge, C.H. Nucleotide accumulation in Staphylococcus aureus by glycine. *J. Bacteriol.* **89** (1965) 1124–1127.

239. Hishinuma, F., Izaki, K. & Takahashi, H. Inhibition of L-alanine adding enzyme by glycine. *Agric. Biol. Chem.* **35** (1971) 2050–2058.

240. Kikuchi, G., Motokawa, Y., Yoshida, T. & Hiraga, K. Glycine cleavage system: reaction mechanism, physiological significance, and hyperglycinemia. *Proc. Jap. Acad. Ser. B Phys. Biol. Sci.* **84** (2008) 246–63.

241. Copp, A.J., Stanier, P. & Greene, N.D. Neural tube defects: recent advances, unsolved questions, and controversies. *Lancet Neurol.* **12** (2013) 799–810.

242. Greene, N.D. & Copp, A.J. Neural tube defects. *A. Rev. Neurosci.* **37** (2014) 221– 242.

243. Pai, Y.J., Leung, K.Y., Savery, D., Hutchin, T., Prunty, H., Heales, S., Brosnan, M.E., Brosnan, J.T., Copp, A.J. & Greene, ND. Glycine decarboxylase deficiency causes neural tube defects and features of non-ketotic hyperglycinemia in mice. *Nature Commun.* **6** (2015) 6388.

244. Mandal, M., Lee, M., Barrick, J.E., Weinberg, Z., Emilsson, G.M., Ruzzo, W.L. & Breaker, R.R. A glycine-dependent riboswitch that uses cooperative binding to control gene expression. *Science* **306** (2004) 275–279.

245. Wiesner, J. & Vilcinskas, A. Antimicrobial peptides. The ancient arm of the human immune system. *Virulence* **1** (2010) 440–464.

246. Zasloff, M. Antimicrobial peptides of multicellular organisms. *Nature* **415** (2002) 389– 395

247. Zhao, L., Ericksen, B., Wu, X., Zhan, C., Yuan, W., Li, X., Pazgier, M. & Lu, W. Invariant Gly residue is important for α-defensin folding, dimerization, and function: A case study of the human neutrophil αf-defensin HNP1. *J. Biol. Chem.* **287** (2012) 18900–18912.

248. Hendriks, W.J.A.J. & Rafael Pulido, R. Protein tyrosine phosphatase variants in human hereditary disorders and disease susceptibilities. *Biochim. Biophys. Acta* **1832** (2013) 1673–1696.

249. Ip, Y.T.& Davis, R.J. Signal transduction by the c-Jun N-terminal kinase (JNK)—from inflammation to development. *Curr. Opinion Cell Biol.* **10** (1998) 205–219.

250. Manganaro, L., Lusic, M., Gutierrez, M.I., Cereseto, A. & Del Sal Mauro Giacca, G. Concerted action of cellular JNK and Pin1 restricts HIV-1 genome integration to activated CD4+ T lymphocytes. *Nature Med.* **16** (2010) 329–333.

251. Tsou, C.L. The role of active site flexibility in enzyme catalysis. *Biochemistry* (Moscow) **63** (1998) 253–258.

252. Alonso, A., Saxena, M., Williams, S. & Mustelin, T. Inhibitory role for dual specificity phosphatase VHR in T cell antigen receptor and CD28-induced Erk and Jnk activation. *J. Biol. Chem.* **276** (2001) 4766–4771.

253. Stahtea, X.N., Kousidou, O.C., Roussidis, A.E., Tzanakakis, G.N. & Karamanos, N.K. Small tyrosine kinase inhibitors as key molecules in the expression of metalloproteinases by solid tumors. *Connective Tissue Res.* **49** (2008) 211–214.

254. Deybach, J.-C., Puy, H., Robréau, A.-M., Lamoril, J., Da Silva, V., Grandchamp, B. & Nordmann, Y. Mutations in the protoporphyrinogen oxidase gene in patients with variegate porphyria. *Hum. Molec. Genet.* **5** (1996) 407–410.

255. Casanova-González, M.J., Trapero-Marugán, M., Jones, E.A. & Moreno-Otero. R. Liver disease and erythropoietic protoporphyria: A concise review. *World J. Gastroenterol.* **16** (2010) 4526–4531.

256. Miller, M.J. Syntheses and therapeutic potential of hydroxamic acid based siderophores and analogues. *Chem. Rev.* **89** (1989) 1563–1579.

257. Kö ster, W. & Böhm, B. Point mutations in two conserved glycine residues within the integral membrane protein Fh affect iron(III) hydroxamate transport. *Molec. Gen. Genet.* **232** (1992) 399–407.

258. Miethke, M., Westers, H., Blom, E.-J., Kuipers, O.P. & Marahiel, M.A. Iron starvation triggers the stringent response and induces amino acid biosynthesis for bacillibactin production in *Bacillus subtilis*. *J. Bacteriol.* **188** (2006) 8655–8657.

259. Lieberthal, W. & Nigam, S.K. Acute renal failure. II. Experimental models of acute renal failure: imperfect but indispensable. *Am. J. Physiol. Renal Physiol.* **278** (2000) F1–F12.

260. Bonventre, J.V. Dedifferentiation and proliferation of surviving epithelial cells in acute renal failure. *J. Am. Soc. Nephrol.* **14** (Suppl. 1) (2003) S55–S61.

261. Schrier, R.W., Wang, W., Poole, B. & Mitra, A. Acute renal failure: definitions, diagnosis, pathogenesis, and therapy. *J. Clin. Investigation* **114** (2004) 5–14.

262. Jayasumana, C., Gunatilake, S. & Senanayake, P. Glyphosate, hard water and nephrotoxic metals: Are they the culprits behind the epidemic of chronic kidney disease of unknown etiology in Sri Lanka? *Intl J. Environ. Res. Public Health* **11** (2014) 2125–2147.

263. Mori, K., Lee, H.T., Rapoport, D., Drexler, I.R., Foster, K., Yang, J., Schmidt-Ott, K.M., Chen, X., Li, J.Y., Weiss, S., Mishra, J., Cheema, F.H., Markowitz, G., Suganami, T., Sawai, K., Mukoyama, M., Kunis, C., d'Agati, V., Devarajan, P. & Barasch, J. Endocytic delivery of lipocalin-siderophore-iron complex rescues the kidney from ischemiareperfusion injury. *J. Clin. Investigation* **115** (2005) 610–621.

264. Halliwell, B. & Gutteridge, J.M. Role of free radicals and catalytic metal ions in human disease: an overview. *Methods Enzymol.* **186** (1990) 1–85.

265. McCord, J.M. Oxygen-derived free radicals in postischemic tissue injury. *N. Engl. J. Med.* **312** (1985) 159–163.

266. Meneghini, R. Iron homeos tasis, oxidative stress, and DNA damage. *Free Radical Biol. Med.* **23** (1997) 783–792.

267. Rangachari, K., Jeyalaxmi, J., Eswari Pandaranayaka, P.J., Prasanthi, N., Sundaresan, P., Krishnadas, S.R. & Krishnaswamy, S. Significance of G-X-W motif in the myocilin olfactomedin domain. *J. Ocular Biol. Dis. Informatics* **4** (2011) 154–158.

268. Lozoff, B. & Georgieff, M.K. Iron deficiency and brain development. *Seminars Pediatr Neurol.* **13** (2006) 158–165.

269. McClung, J.P. & Karl, J.P. Iron deficiency and obesity: the contribution of inflammation and diminished iron absorption. *Nutrition Reviews* **67** (2009) 100–104.

270. Ostberg, K.L., DeRocco, A.J., Mistry, S.D., Dickinson, M.K. & Cornelissen, C.N. Conserved regions of gonococcal TbpB are critical for surface exposure and transferrin iron utilization. *Infect. Immun.* **81** (2013) 3442–3450.

271. Y asuda, E., Ebinuma, H. & Wabiko, H. A novel glycine-rich/hydrophobic 16 kDa polypeptide gene from tobacco: similarity to proline-rich protein genes and its woundinducible and developmentally regulated expression. *Plant Molec. Biol.* **33** (1997) 667–678.

272. W ilson, K.A., Bär, S., Maerz, A.L., Alizon, M. & Poumbourios, P. The conserved glycine-rich segment linking the N-terminal fusion peptide to the coiled coil of human Tcell leukemia virus type 1 transmembrane glycoprotein gp21 is a determinant of membrane fusion function. *J. Virol.* **79** (2005) 4533–4539.

273. Hietanen, E., Linnainmaa, K. & Vainio, H. Effects of phenoxyherbicides and glyphosate on the hepatic and intestinal biotransformation activities in the rat. *Acta Pharmacol. Toxicol.* (Copenhagen) **53** (1983) 103–112.

274. Gonzalez, F.J. The molecular biology of cytochrome P450. *Pharmacol. Rev.* **40** (1989) 243–288.

275. Y amazaki, S., Sato, K., Suhara, K., Sakaguchi, M., Michara, K. & Omura, T. Importance of the proline-rich region following signal-anchor sequence in the formation of correct conformation of microsomal cytochrome P-450s. *J. Biochem.* **114** (1993) 652–657.

276. Chen, C.D. & Kemper, B. Different structural requirements at specific proline rich residue positions in the conserved proline-rich region of cytochrome P4502C2. *J. Biol. Chem.* **271** (1996) 28607–28611.

277. S toilov, I., Akarsu, A.N., Alozie, I., Child, A., Barsoum-Homsy, M., Turacli, M.E., Or, M., Lewis, R.A., Ozdemir, N., Brice, G., Aktan, S.G., Chevrette, L., Coca-Prados, M. & Sarfarazi, M. Sequence analysis and homology modeling suggest that primary congenital glaucoma on 2p21 results from mutations disrupting either the hinge region or the conserved core structures of cytochrome P4501B1. *Am. J. Hum. Genet.* **62** (1998) 573–584.

278. Bejjani, B.A., Lewis, R.A., Tomey, K.F., Anderson, K.L., Dueker, D.K., Jabak, M., Astle, W.F., Otterud, B., Leppert, M. & Lupski, J.R. Mutations in CYP1B1, the gene for cytochrome P4501B1, are the predominant cause of primary congenital glaucoma in Saudi Arabia. *Am. J. Hum. Genet.* **62** (1998) 325–333.

279. Shoulders, M.D. & Raines, R.T. Collagen structure and stability. *A. Rev. Biochem.* **78** (2009) 929–958.

280. Pace, J.M., Atkinson, M., Willing, M.C., Wallis, G. & Byers, P.H. Deletions and duplications of Gly-Xaa-Yaa triplet repeats in the triple helical domains of type I collagen chains disrupt helix formation and result in several types of osteogenesis imperfecta. *Hum. Mutation* **18** (2001) 319–326.

281. Beck, K., Chan, V.C., Shenoy, N., Kirkpatrick, A., Ramshaw, J.A.M. & Brodsky, B. Destabilization of osteogenesis imperfecta collagen-like model peptides correlates with the identity of the residue replacing glycine. *Proc. Natl Acad. Sci. USA* **97** (2000) 4273–4278.

282. Bodian, D.L., Madhan, B., Brodsky, B. & Klein, T.E. Predicting the clinical lethality of osteogenesis imperfecta from collagen glycine mutations. *Biochemistry* **47** (2008) 5424– 5432.

283. Nuytinck, L., Tükel, T., Kayserili, H., Apak, M.Y. & De Paepe, A. Glycine to tryptophan substitution in type I collagen in a patient with OI type III: a unique collagen mutation. *J. Med. Genet.* **37** (2000) 371–375.

284. Marini, J.C., Forlino, A., Cabral, W.A., Barnes, A.M., San Antonio, J.D., Milgrom, S., Hyland, J.C., Körkkö, J., Prockop, D.J., De Paepe, A., Coucke, P., Symoens, S., Glorieux, F.H., Roughley, P.J., Lund, A.M., Kuurila-Svahn, K., Hartikka, H., Cohn, D.H., Krakowk D., Mottes, M., Schwarze, U., Chen, D., Yang, K., Kuslich, C., Troendle, J., Dalgleish, R. & Byers, P.H. Consortium for osteogenesis

imperfecta mutations in the helical domain of type I collagen: regions rich in lethal mutations align with collagen binding sites for integrins and proteoglycans. *Hum. Mutation* **28** (2007) 209–221.

285. Gill, J.R., Goldfeder, L.B., Armbrustmacher, V., Coleman, A., Mena, H. & Hirsch, C.S. Fatal head injury in children younger than 2 years in New York City and an overview of the shaken baby syndrome. *Arch. Pathol. Lab. Med.* **133** (2009) 619–627.
286. Hamdy, R.C. Osteoporosis, the deafening silent epidemic. *South Med. J.* **95**(6) (2002) 567–568.
287. Keen, R.W. Burden of osteoporosis and fractures. *Curr. Osteoporosis Rep.* **1** (2003) 66–70.
288. Schinasi, L., Leon, M.E. Non-Hodgkin lymphoma and occupational exposure to agricultural pesticide chemical groups and active ingredients: a systematic review and metaanalysis. *Intl J. Environ Res. Publ. Health* **11** (2014) 4449–4527.
289. Eriksson, M., Hardell, L., Carlberg, M. & Akerman, M. Pesticide exposure as risk factor for non-Hodgkin lymphoma including histopathological subgroup analysis. *Intl J. Cancer* **123** (2008) 16571663.
290. Freedman, A.S., Munro, J.M., Morimoto, C., McIntyre, B.W., Rhynhart, K., Lee, N. & Nadler, L.M. Follicular non-Hodgkin's lymphoma cell adhesion to normal germinal centers and neoplastic follicles involves very late antigen-4 and vascular cell adhesion molecule-1. *Blood* **79** (1992) 206–212.
291. Arroyo, A.G., Yang, J.T., Rayburn, H. & Hynes, R.O. Alpha4 integrins regulate the proliferation/differentiation balance of multilineage hematopoietic progenitors in vivo. *Immunity* **11** (1999) 555–566.
292. Guerrero-Esteo, M., Ruiz-Velasco, N., Muñoz, M. & Teixidó, J. Role of two conserved glycine residues in the beta-propeller domain of the integrin alpha4 subunit in VLA-4 conformation and function. *FEBS Lett.* **429** (1998) 123–128.
293. Poulsen, M.S., Rytting, E., Mose, T. & Knudsen, L.E. Modeling placental transport: correlation of in vitro BeWo cell permeability and ex vivo human placental perfusion. *Toxicol. in Vitro* **23** (2009) 1380–1386.
294. Campana, H., Pawluk, M.S. & Lopez Camelo, J.S. [Births prevalence of 27 selected congenital anomalies in 7 geographic regions of Argentina]. *Arch. Argent. Pediat.* **108** (2010) 409–417.
295. Benitez Leite, S., Macchi, M.A. & Acosta, M. Malformaciones Congenitas asociadas a agrotoxicos. *Arch. Pediat. Drug* **80** (2009) 237–247.
296. Person, A., Spitters, C., Patrick, G., Wasserman, C., Vander Kelen, P., VanEenwyk, J., Gilboa, S., Kucik, J., Sorenson, R., Ailes, E. & Stahre, M. Notes from the field: Investigation of a cluster of neural tube defects—Central Washington, 2010–2013. *Morbidity Mortality Weekly Rep.* (MMWR) **62** (2013) 728–728
297. Roy, N.M., Carneiro, B. & Ochs, J. Glyphosate induces neurotoxicity in zebrafish. *Environ. Toxicol. Pharmacol.* (2016); In Press. doi:10.1016/j.etap.2016.01.003.
298. Adachi, Y., Mochida, G., Walsh, C. & Barkovich, J. Posterior fossa in primary microcephaly: relationships between forebrain and mid-hindbrain size in 110 patients. *Neuropediatrics* **45** (2014) 93–101.
299. Paganelli, A., Gnazzo, V., Acosta, H., López, S.L. & Carrasco, A.E. Glyphosate-based herbicides produce teratogenic effects on vertebrates by impairing retinoic acid signaling. *Chem. Res. Toxicol.* **23** (2010) 1586–1595.
300. Shen, J., Gilmore, E.C., Marshall, C.A., Haddadin, M., Reynolds, J.J., Eyaid, W., Bodell, A., Barry, B., Gleason, D., Allen, K., Ganesh, V.S., Chang, B.S., Grix, A., Hill, R.S., Topcu, M., Caldecott, K.W., Barkovich, A.J. & Walsh, C.A. Mutations in PNKP cause microcephaly, seizures and defects in DNA repair. *Nature Genet.* **42** (2010) 245–249.
301. Reynolds, J.J., Walker, A.K., Gilmore, E.C., Walsh, C.A. & Caldecott, K.W. Impact of PNKP mutations associated with microcephaly, seizures and developmental delay on enzyme activity and DNA strand break repair. *Nucl. Acids Res.* **40**(14) (2012) 6608–6619.
302. Narisawa, A., Komatsuzaki, S., Kikuchi, A., Niihori, T., Aoki, Y., Fujiwara, K., Tanemura, M., Hata, A., Suzuki, Y., Relton, C.L., Grinham, J., Leung, K.Y., Partridge, D., Robinson, A., Stone, V., Gustavsson, P., Stanier, P., Copp, A.J., Greene, N.D., Tominaga, T., Matsubara, Y. & Kure, S. Mutations in genes encoding the glycine cleavage system predispose to neural tube defects in mice and humans. *Hum. Molec. Genet.* **21** (2012) 1496–1503.
303. Crider, K.S., Bailey, L.B. & Berry1, R.J. Folic acid food fortification—its history, effect, concerns, and future directions. *Nutrients* **3** (2011) 370–384.
304. Holländer, H. & Amrhein, N. The site of the inhibition of the shikimate pathway by glyphosate I. Inhibition by glyphosate of phenylpropanoid synthesis in buckwheat (Fagopyrum esculentum moench). *Plant Physiol.* **66** (1980) 823–829.
305. Hartzell, S. & Seneff, S. Impaired sulfate metabolism and epigenetics: Is there a link in autism? *Entropy* **14** (2012) 1953–1977.
306. James, S.J., Cutler, P., Melnyk, S., Jernigan, S., Janak, L., Gaylor, D.W. & Neubrander, J.A. Metabolic biomarkers of increased oxidative stress and impaired methylation capacity in children with autism. *Am. J. Clin. Nutr.* **80** (2004) 1611–1617.
307. Kume, A., Koyata, H., Sakakibara, T., Ishiguro, Y., Kure, S. & Hiraga, K. The glycine cleavage system: Molecular cloning of the chicken and human glycine decarboxylase cDNAs and some characteristics involved in the deduced protein structures. *J. Biol. Chem.* **266** (1991) 3323–3329.
308. Gilmore, J.H., Smith, L.C., Wolfe, H.M., Hertzberg, B.S., Smith, J.K., Chescheir, N.C., Evans, D.D., Kang, C., Hamer, R.M., Lin, W. & Gerig, G. Prenatal mild ventriculomegaly predicts abnormal development of the neonatal brain. *Biol. Psychiat.* **64** (2008) 1069–1076.
309. Bonilha, L., Cendes, F., Rorden, C., Eckert, M., Dalgalarrondo, P., Li, L.M. & Steiner, C.E. Gray and white matter imbalance—typical structural abnormality underlying classic autism? *Brain Dev.* **30** (2008) 396–401.
310. Yu, T.W., Chahrour, M.H., Coulter, M.E., Jiralerspong, S., Okamura-Ikeda, K., Ataman, B., Schmitz-Abe, K., Harmin, D.A., Adli, M., Malik, A.N., D'Gama, A.M., Lim, E.T., Sanders, S.J., Mochida, G.H., Partlow, J.N., Sunu, C.M., Felie JM, Rodriguez, J., Nasir, R.H., Ware, J., Joseph, R.M., Hill, R.S., Kwan, B.Y., Al-Saffar, M., Mukaddes, N.M., Hashmi, A., Balkhy, S., Gascon, G.G., Hisama, F.M., LeClair, E., Poduri, A., Oner, O., Al-Saad, S., Al-Awadi, S.A., Bastaki, L., Ben-Omran, T., Teebi, A.S., Al-Gazali, L., Eapen,

V., Stevens, C.R., Rappaport, L., Gabriel, S.B., Markianos, K., State, M.W., Greenberg, M.E., Taniguchi, H., Braverman, N.E., Morrow, E.M. & Walsh, C.A. Using whole-exome sequencing to identify inherited causes of autism. *Neuron* **77** (2013) 259–273.

311. Kure, S., Kato, K., Dinopoulos, A., Gail, C., DeGrauw, T.J., Christodoulou, J., Bzduch, V., Kalmanchey, R., Fekete, G., Trojovsky, A., Plecko, B., Breningstall, G., Tohyama, J., Aoki, Y. & Matsubara, Y. Comprehensive mutation analysis of GLDC, AMT, and GCSH in nonketotic hyperglycinemia. *Hum. Mutation* **27** (2006) 343–352.
312. Lin, F.Y., Gascon, G.G., Hyland, K., Chugani, H. & Chugani, D. Transient nonketotic hyperglycinemia and defective serotonin metabolism in a child with neonatal seizures. *J. Child Neurol.* **21** (2006) 900–903.
313. Grishin, N.V., Phillips, M.A. & Goldsmith, E.J. Modeling of the spatial structure of eukaryotic ornithine decarboxylases. *Protein Sci.* **4** (1995) 1291–1304.
314. Pendeville, H., Carpino, N., Marine, J.C., Takahashi, Y., Muller, M., Martial, J.A. & Cleveland, J.L. The ornithine decarboxylase gene is essential for cell survival during early murine development. *Molec. Cell. Biol* **21** (2001) 654958.
315. Tuchman, R. & Rapin, I. Epilepsy in autism. *Lancet Neurol.* **1** (2002) 352358.
316. Herberg, L.J., Rose, I.C., de Belleroche, J.S. & Mintz, M. Ornithine decarboxylase induction and polyamine synthesis in the kindling of seizures: the effect of alpha-difluoromethylornithine. *Epilepsy Res.* **11** (1992) 37.
317. Islam, M.I., Hoque, S.K., Islam, M.T., Saha N.C., Matin, A., Rahman, A.A. & Saleh, A.S.M. Vanishing white matter disease: A case report. *Bangladesh J. Child Health* **35** (2011) 127–129.
318. van der Knaap, M.S., van Berkel, C.G., Herms, J., van Coster, R., Baethmann, M., Naidu, S., Boltshauser, E., Willemsen, M.A., Plecko ,B., Hoffmann, G.F., Proud, C.G., Scheper, G.C. & Pronk, J.C. eIF2B related disorders: antenatal onset and involvement of multiple organs. *Am. J. Hum. Genet.* **73** (2003) 1199–1207.
319. Vermeulen, G., Seidl, R., Mercimek-Mahmutoglu, S., Rotteveel, J.J., Scheper, G.C.& van der Knaap, M.S. Fright is a provoking factor in vanishing white matter disease. *Ann. Neurol.* **57** (2005) 560–563.
320. Kirsch, J. & Betz, H. Glycine-receptor activation is required for receptor clustering in spinal neurons. *Nature* **392** (1998) 717–720.
321. Lynch, J.W. Molecular structure and function of the glycine receptor chloride channel. *Physiol. Rev.* **84** (2004) 1051–1095.
322. Atak, S., Langlhofer, G., Schaefer, N., Kessler, D., Meiselbach, H., Delto, C., Schindelin, H. & Villmann, C. Disturbances of ligand potency and enhanced degradation of the human glycine receptor at affected positions G160 and T162 originally identified in patients suffering from hyperekplexia. *Frontiers Molec. Neurosci.* **8** (2015) 79.
323. Vandenberg, R.J., French, C.R., Barry, P.H., Shine, J. & Schofield, P.R. Antagonism of ligand-gated ion channel receptors: Two domains of the glycine receptor α subunit form the strychnine-binding site. *Proc. Natl Acad. Sci. USA* **89** (1992) 1765–1769.
324. Coullery, R.P., Ferrari, M.E. & Rosso, S.B. Neuronal development and axon growth are altered by glyphosate through a WNT non-canonical signaling pathway. *Neurotoxicology* **52** (2015) 150–161.
325. Yilmaz, M., Gangopadhyay, S.S., Leavis, P., Grabarek, Z. & Morgan, K.G. Phosphorylation at Ser26 in the ATP-binding site of Ca^{2+}/calmodulin-dependent kinase II as a mechanism for switching off the kinase activity. *Biosci. Rep.* **33** (2013) e00024.
326. Iacono, K.T., Brown, A.L., Greene, M.I. & Saouaf, S.J. CD147 immunoglobulin superfamily receptor function and role in pathology. *Exp. Molec. Pathol.* **83** (2007) 283–295.
327. Zhou, S., Zhou, H., Walian, P.J. & Jap, B.K. CD147 is a regulatory subunit of the gamma-secretase complex in Alzheimer's disease amyloid beta-peptide production. *Proc. Natl Acad. Sci. USA* **102** (2005) 7499–7504.
328. Naruhashi, K., Kadomatsu, K., Igakura, T., Fan, Q.W., Kuno, N., Muramatsu, H., Miyauchi, T., Hasegawa, T., Itoh, A., Muramatsu, T. & Nabeshima, T. Abnormalities of sensory and memory functions in mice lacking Bsg gene. *Biochem. Biophys. Res. Commun.* **236** (1997) 733–737.
329. Igaku ra, T., Kadomatsu, K., Kaname, T., Muramatsu, H., Fan, Q.W., Miyauchi, T., Toyama, Y., Kuno, N., Yuasa, S., Takahashi, M., Senda, T., Taguchi, O., Yamamura, K., Arimura, K. & Muramatsu, T. A null mutation in basigin, an immunoglobulin superfamily member, indicates its important roles in peri-implantation development and spermatogenesis. *Devl Biol.* **194** (1998) 152–165.
330. Lu, W., Li, L., Chen, M., Zhou, Z., Zhang, W., Ping, S., Yan, Y., Wang, J. & Lin, M. Genome-wide transcriptional responses of Escherichia coli to glyphosate, a potent inhibitor of the shikimate pathway enzyme 5-enolpyruvylshikimate-3-phosphate synthase. *Molec. BioSyst* **9** (2013) 522–530. Supplementary Table S2: Functional description of genes downregulated in response to glyphosate shock.
331. Deyrup, A.T., Krishnan, S., Cockburn, B.N. & Schwartz, NB. Deletion and sitedirected mutagenesis of the ATP-binding motif (p-loop) in the bifunctional murine ATPsulfurylase/adenosine 5'-phosphosulfate kinase enzyme. *J. Biol. Chem.* **273** (1998) 9450–9456.
332. van den Boom, J., Heider, D., Martin, S.R., Pastore, A. & Mueller, J.W. 3-Phosphoadenosine 5-phosphosulfate (PAPS) synthases, naturally fragile enzymes specifically stabilized by nucleotide binding. *J. Biol. Chem.* **287** (2012) 17645–17655.
333. Therien, A.G.& Deber, C.M. Oligomerization of a peptide derived from the transmembrane region of the sodium pump gamma subunit: effect of the pathological mutation G41R. *J. Molec. Biol.* **322** (2002) 583–550.
334. Konrad, M. & Schlingmann, K.P. Inherited disorders of renal hypomagnesaemia. *Nephrol. Dialysis Transplantation* **29** (2014) iv63–iv71.
335. Nassi, P., Nediani, C., Fiorillo, C., Marchetti, E., Liguri, G.& Ramponi, G. Modifications induced by acylphosphatase in the functional properties of heart sarcolemma Na^+,K^+ pump. *FEBS Lett.* **337** (1994) 109–113.
336. Nedi ani, C., Celli, A., Formigli, L., Perna, A.M., Fiorillo, C., Ponziani, V., Ibba- Manneschi, L., Zecchi-Orlandini, S., Nosi, D., Liguri, G., Modesti, P.A.& Nassi, P. Possible role of acylphosphatase, Bcl-2 and Fas/Fas-L system in the early changes of cardiac remodeling induced by volume overload. *Biochim. Biophys. Acta* **1638** (2003) 217–226.
337. Dongre, M., Singh, N.S., Dureja, C., Peddada, N., Solanki,

A.K., Ashish & Raychaudhuri, S. Evidence on How a Conserved Glycine in the Hinge Region of HapR Regulates Its DNA Binding Ability. Lessons from a natural variant. *J. Biol. Chem.* **286** (2011) 15043–15049.

338. Beach, M.J. & Rodwell, V.W. Cloning, sequencing, and overexpression of mvaA, which encodes Pseudomonas mevalonii 3-hydroxy-3-methylglutaryl coenzyme A reductase. *J. Bacteriol.* **171** (1989) 2994–3001.

339. Liang, C. & Needham, M. Necrotizing autoimmune myopathy. *Curr. Opin. Rheumatol.* **23** (2011) 612–619.

340. Hack, R., Ebert, E., Ehling, G. & Leist, K.-H. Glufosinate ammonium—Some aspects of its mode of action in mammals. *Food Chem. Toxicol.* **32** (1994) 461–470.

341. Watanabe, T. & Iwase, T. Developmental and dysmorphogenic effects of glufosinate ammonium on mouse embryos in culture. *Teratog Carcinog Mutagen* **16** (1996) 287–299.

342. Fujii, T., Ohata, T. & Horinaka, M. Alternations in the response to kainic acid in rats exposed to glufosinate-ammonium, a herbicide, during infantile period. *Proc. Jap. Acad. Ser. B Phys. Biol. Sci.* **72** (1996) 7–10.

343. Laugeray, A., Herzine, A., Perche, O., Hébert, B., Aguillon-Naury, M., Richard, O., Menuet, A., Mazaud-Guittot, S., Lesné, L., Briault, S., Jegou, B., Pichon, J., Montécot-Dubourg, C. & Mortaud, S. Pre- and postnatal exposure to low dose glufosinate ammonium induces autism-like phenotypes in mice. *Frontiers Behavioral Neurosci.* **8** (2014) 390.

344. Yang, P. & Chang, C.L. Glutamate-mediated signaling and autism spectrum disorders: emerging treatment targets. *Curr. Pharmaceutical Design* **20** (2014) 5186–5193.

345. Ruzzo, E.K., Capo-Chichi, J.M., Ben-Zeev, B., Chitayat, D., Mao, H., Pappas, A.L., Hitomi, Y., Lu, Y.F., Yao, X., Hamdan, F.F., Pelak, K., Reznik-Wolf, H., Bar-Joseph, I., Oz-Levi, D., Lev, D., Lerman-Sagie, T., Leshinsky-Silver, E., Anikster, Y., Ben-Asher, E., Olender, T., Colleaux, L., Décarie, J.C., Blaser, S., Banwell, B., Joshi, R.B., He, X.P., Patry, L., Silver, R.J., Dobrzeniecka, S., Islam, M.S., Hasnat, A., Samuels, M.E., Aryal, D.K., Rodriguiz, R.M., Jiang, Y.H., Wetsel, W.C., McNamara, J.O., Rouleau, G.A., Silver, D.L., Lancet, D., Pras, E., Mitchell, G.A., Michaud, J.L. & Goldstein, D.B. Deficiency of asparagine synthetase causes congenital microcephaly and a progressive form of encephalopathy. *Neuron* **80** (2013) 429–441.

346. Meyer, M.E., Gutierrez, J.A., Raushel, F.M. & Richards, N.G. A conserved glutamate controls the commitment to acyl-adenylate formation in asparagine synthetase. *Biochemistry* **49** (2010) 9391–9401.

347. Yool, A.J. Dominant-negative suppression of big brain ion channel activity by mutation of a conserved glutamate in the first transmembrane domain. *Gene Expression* **13** (2007) 329–337.

348. Männikkö, R., Flanagan, S.E., Sim, X., Segal, D., Hussain, K., Ellard, S., Hattersley, A.T. & Ashcroft, F.M. Mutations of the same conserved glutamate residue in NBD2 of the sulfonylurea receptor 1 subunit of the KATP channel can result in either hyperinsulinismor neonatal diabetes. *Diabetes* **60** (2011) 1813–1822.

349. Polak, M. & Cavé, H. Neonatal diabetes mellitus: A disease linked to multiple mechanisms. *Orphanet J. Rare Dis.* **2** (2007) 12.

350. Larsson, H.P. & Elinder, F. A conserved glutamate is important for slow inactivation in K^+ channels. *Neuron* **27** (2000) 573–583.

351. Hanson, P.I. & Whiteheart, S.W. AAA+ proteins: have engine, will work. *Nature Rev. Molec. Cell Biol.* **6** (2005) 519–529.

352. Chiraniya, A., Finkelstein, J., O'Donnell, M. & Bloom, L.B. A novel function for the conserved glutamate residue in the WalkerB motif of replication factor C. *Genes* **4** (2013) 134–151.

353. Narayanan, A.S., Page, R.C. & Swanson, J. Collagen synthesis by human fibroblasts. Regulation by transforming growth factor-β in the presence of other inflammatory mediators. *Biochem. J.* **260** (1989) 463–469.